The Impact of Kinetic Façade on the Performance and Energy Efficiency of a Public Building in Dubai

The Case of Dubai Frame

تأثير الواجهات الحركية على الأداء والكفاءة في استخدام الطاقة لمبنى عام في دبي
حالة دراسية على برواز دبي

by

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Dissertation submitted in fulfilment

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Abstract

Recently many studies were conducted to discuss adaptive and intelligent façade techniques in response to climate factors to enhance the sustainability measures of buildings. However, these studies have not been interacted in the design stage of buildings especially in the cities of Dubai and Abu Dhabi, where there are many high-rise buildings that consist of large percentage of glazing in their façade, which increase the amount of energy consumption and affect the performance of these buildings.

The aim of this research is to optimise the sustainability of a public building by applying a kinetic system and a design strategy that response to three indicators; electricity and cooling loads, sun exposure and the aesthetic values of the building. Moreover, this research validates the use of Integrated Environmental Solutions (IES VE software) to be accredited for Dubai Municipality green building evaluation system (Safat) in assessing the performance of buildings through the design process of innovative technologies, which is achieved by validating IES results in comparison to the conducted field measurements using a special equipment from the sustainability department of the British University in Dubai.

This research introduces a new concept of shading systems and discusses the main parameters of kinetic design principles and strategies to generate an optimal solution and result in getting a better rating of the building through Sa'fat indicators.

In addition, a basic model that consist of perforated fixed façade and a proposed model with kinetic shading system will be compared to demonstrate that the implementation of new innovative systems and techniques will be an efficient strategy to enhance the performance of the building while preserving its architectural concepts.

The research has reached several important results. For example, the optimal kinetic system results in 20% energy savings and 31% reduction in daylighting illuminance levels while taking into account the current situation of the building and its aesthetic values. The results of this research will benefit engineers and designers to design buildings with efficient energy both inside the UAE and abroad from countries that has the same climatic conditions.

ملخص

تم مؤخرًا إجراء العديد من الدراسات لمناقشة تقنيات الواجهات المكيفة الذكية استجابةً للعوامل المناخية لتعزيز مقاييس استدامة المباني. ومع ذلك ، لم تتفاعل هذه الدراسات في مرحلة تصميم المباني خاصة في مدينتي دبي وأبو ظبي ، حيث توجد العديد من المباني العالية التي تتكون من نسبة كبيرة من الزجاج في واجهاتها ، مما يزيد من استهلاك الطاقة و يؤثر على أداءها.

يهدف هذا البحث إلى تحسين استدامة المباني العامة من تطبيق نظام حركي واستراتيجية تصميم تستجيب لثلاثة مؤشرات ؛ أحمال الكهرباء والتبريد والتعرض لأشعة الشمس والقيم الجمالية للمبنى. سيتم من خلال هذا البحث التحقق من صحة استخدام برنامج IES VE ليتم اعتماده في نظام تقييم المباني الخضراء التابع لبلدية دبي (السعفات) لتقييم أداء المباني في مرحلة التصميم للمشاريع المبتكرة . سيتم تحقيق ذلك من خلال التحقق من صحة نتائج IES بالمقارنة مع قياسات الموقع التي سيتم إجراؤها باستخدام معدات خاصة من قسم الاستدامة في الجامعة البريطانية في دبي. من ناحية أخرى، فإن معايرة فواتير استهلاك الطاقة الحالية ستكون مفيدة لتقييم استهلاك الطاقة في المبنى المحدد.

يقدم هذا البحث مفهومًا جديدًا لأنظمة التظليل ويناقش المعالم الرئيسية لمبادئ واستراتيجيات التصميم الحركي لتحقيق الحل الأمثل والوصول إلى تصنيف أفضل للبناء من خلال مؤشرات السعفات.

الإضافة إلى ذلك ، سيتم إجراء مقارنة بين النموذج الأساسي الذي يتكون من واجهة ثابتة مثقبة والنموذج المقترح مع نظام التظليل الحركي لإثبات أن تنفيذ أنظمة وتقنيات مبتكرة جديدة ستكون استراتيجية فعالة لتعزيز أداء المبنى مع الحفاظ على المفاهيم المعمارية فقد توصل البحث الى عدة نتائج مهمة اهمها تخفيض استهلاك الطاقة بنسبة تصل الى 20٪ و خفض بنسبة 31 ٪ في مستويات الإضاءة في ضوء النهار وذلك مع مراعاة الوضع الحالي للمبنى و مكانته الساحية. ان نتائج هذا البحث ستفيد المهندسين و المصممين الى تصميم مباني ذات طاقة كفء سواء داخل الامارت العربية المتحدة او خارجها من الدول التى تتمتع بنفس المناخ و البيئة.

Dedication

To My Father and My Mother

To My Husband

Acknowledgment

I wish to express my deepest gratitude to my principal supervisor, Dr. Hanan Talab for her advice, immense encouragement, guidance and trust throughout the period of this research.

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Special thanks to my father for English proofing this dissertation, my brother Laith for assisting me in using Excel techniques for analysing the research results, my dear friend Mais for introducing me to Grasshopper and assisting me in coding the parametric model of this project. I am forever indebted for their assistance and the quality of their review.

Most importantly, I wish to thank every member of my family for their continuous support and encouragement during this research work.

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Abbreviations

UAE	United Arab Emirates
CABS	Climate adaptive building shells
BIPV	Building integrated photovoltaic
IEQ	Indoor Environmental Quality
PCM	Phase change materials
TIM	Thermal interface material
ETFE	Ethylene tetrafluoroethylene- fluorine based plastic
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
DGI	Daylight glare index
sDA	Spatial daylight autonomy
HOE	Holographic optical elements
GBC	Green Building Council
CH2	Council House 2
LEED	Leadership in Energy and Environmental Design system
GFRP	Glass fibre reinforced polymers
GB	Green Building
DIVA	Design Iterate Validate Adapt
FIT	Façade Innovative Technology
HVAC	Heating, ventilation and air conditioning
BPS	Building Performance Simulation
FIT	Façade Innovative Technology

RH	Relative Humidity
WWR	Window Wall Ratio
LR	Literature Review
RSMF	Room Surface maintenance factor
LMF	Luminaire maintenance factor
DEWA	Dubai Electricity and Water Authority
VAT	Value added tax
IHG	Internal Heat Gains

CHAPTER ONE

INTRODUCTION

Chapter 1 Introduction

1.1 Background Information

Recent Studies indicated that buildings consume more energy than other sectors such as industrial and transportation sectors. Therefore, the improvement of indoor environment has been developed through the application of air-conditioning, lighting, heating, indoor air quality to adapt with people comfort. However, building envelopes are not able to moderate between achieving the required comfort without the exploitation of energy, which makes building part of the problem of greenhouse emissions and global warming.

Buildings' envelopes have been always used as a shelter to protect people from extreme climate and conditions. Bacha & Bourbia (2016) described the building envelop as barrier between exterior and interior environment where interior environment facilitates thermal comfort and climate control.

Building façade design was traditionally statistic even though the climatic conditions constantly changing. Therefore, kinetic façade has been developed to an alternative building envelope. According to Sharaidin (2014), International Energy Agency (Energy Conservation in Buildings and Community Systems Program) considered that adaptive façade implementation is necessary to improve buildings' energy efficiency levels and react to current environmental conditions.

Kinetic façade has been designed to adapt with the increasing demand of cost efficiency, thermal comfort and energy consumption. Sharaidin (2014) stated that the concept of kinetic façade would range from the usage of advanced mechanisms to complex designs and applications.

This research will present an overview of kinetic façade design strategies, methodologies and design evaluation techniques to develop a performance-based design. This approach is used to demonstrate the challenges of actual façade through the process of testing and evaluating the problems of construction and installing kinetic facades in the building. The approach is used to measure the performance of kinetic façade through simulation tools, which will help designers to understand the limitations of simulation tools and investigate new design techniques.

In addition, this research contributes in presenting design and evaluation techniques of designing Kinetic façade through digital simulation tool. Furthermore, on site experiments and evaluation of existing energy consumption levels of an existing building in Dubai were examined to act as a base case for the proposed design technologies. Based on environmental parameters such as daylight levels, Thermal comfort and the functionality of the building that act as touristic feature with a Viewing Bridge were used to achieve the optimal solution of adaptive façade configuration for the building.

1.2 Global Review

Energy consumption levels have increased rapidly through the past decades. It was stated by Sharaidin (2014) and Nady (2017) that energy consumption levels in the United States shows that buildings' energy consumption has exceeded other sectors due to the amount of time people spend in indoor spaces that would reach 90% of their time. Therefore, Marysse (2016) highlighted that the buildings ecological footprint accounts for 39% where the energy intensive is consumed by HVAC systems as indicated in Figure 1 below.

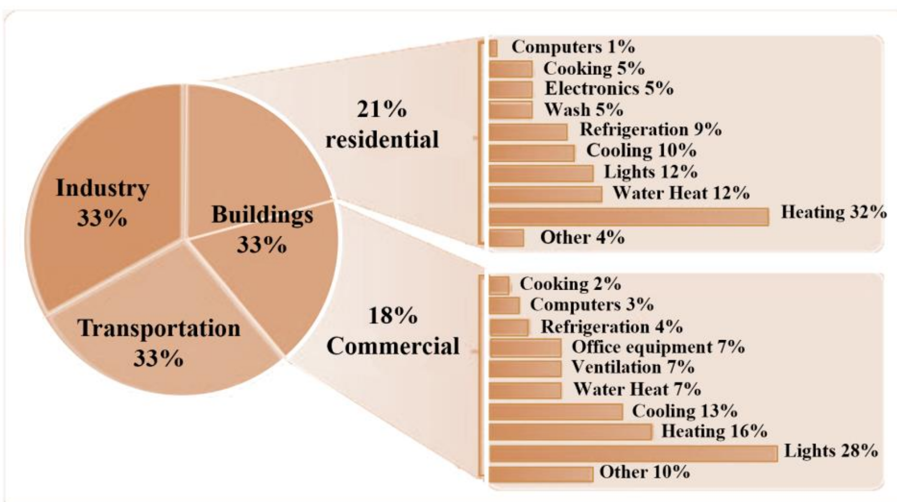


Figure 1: Buildings Ecological footprint, (Marysse 2016)

Moreover, Building and construction sectors have an important role in reducing carbon dioxide and harmful emissions in the environment as it is considered the most energy consuming divisions. Therefore, as indicated by Nady (2017), those sectors have a very high potential to convert to powerful and active sectors through implementing sustainable strategies that make the building an effective and energy-efficient feature. This can be achieved by introducing intelligent and adaptive device that interact with its environment.

On the other hand, figures have indicated that in the US, the buildings consume 41% of energy and 5% is connected to losses and heat gain in the building envelop. Therefore, the focus on zero energy building has increased nationally and became a part of the public policies globally to provide innovative technologies for buildings adaptive systems, (Elzeyadi 2017).

Nevertheless, European regulations have led into scientific research in terms of energy efficiency for construction areas and building's envelopes. Therefore, new systems were adopted to reduce to zero net energy consumption of integrated buildings to improve European cities sustainability for both new and existing buildings, (Romano et al. 2018).

Furthermore, a project called COST Action TU1403 with its network "Adaptive Façade Network" aimed to gather information of adaptive façade, knowledge and technologies of different countries, institutions and industries from 2014 until 2018 to address effective tools for adaptive face and identify the gaps of operational assessment, (Attia 2017).

1.3 UAE and Dubai

Energy efficiency and sustainable strategies is a growing challenge in UAE and Dubai due to many factors; economic activity, population growth and the high rates of energy consumption. In this matter, Dubai and Abu Dhabi has adopted many strategies such as energy-efficient strategies, regulatory frameworks, sustainable events and communication initiatives with stakeholders and residence to reduce their energy consumption.

Figures have indicated that the rapid use of energy consumption has grown to an annual average of 4% and would reach up to 5% in 2020 as indicated in Figure 2. Whereas the overall demand of electricity consumption was doubled during the last 10 years, 70% of this consumption represents the cooling loads of buildings. Therefore, building efficiency measures were promoted through green building regulations such as Estidama and Sa'fat to measure the sustainable performance of building through specific rating systems, (Karlsson, Decker & Moussalli 2015).

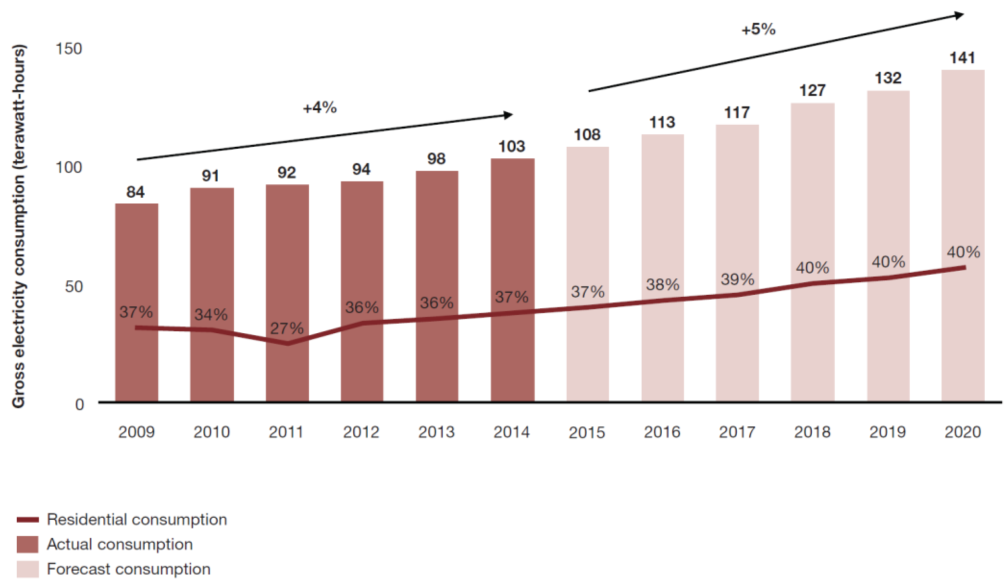


Figure 2: UAE total energy consumption over the past 10 years, (Karlsson, Decker & Moussalli 2015)

On the other hand, UAE and Dubai experience hot and humid climate with a temperature that would reach up to 49 °C with 100% humidity levels during summer, (Attia 2017). Therefore, glazed façade is considered a source of undesired heat gain that results in discomfort for the users of buildings. (Bacha & Bourbia 2016) discussed that the impact of daylight reduction and solar gain affect the performance of employees, which requires enhancement for glazing systems such as using solar control glass and shading strategies to eliminate intense solar exposure and disturbance factors.

Al Sa'fat is the new version of Dubai Green Building evaluation system, which consists of four categories; Bronze Sa'fa, Silver Sa'fa, Golden Sa'fa and Platinum Sa'fa. The first category, Sliver Sa'fa is mandatory for private villas and industrial buildings, the second category, Silver Sa'fa is mandatory for all the other types of buildings whereas the remaining categories are optional.

Energy Models have been developed to simulate the impact of Al Sa'fat; results show that Silver Sa'fa accounts for approximately 7% increase in electricity savings, 26% for Golden Sa'fa and 32% for Platinum Sa'fa. Figure 3 shows the enhancement of each category in electricity savings as indicated by M&E enhancement project provided by Taqati and Dubai Municipality, (Zid 2018).

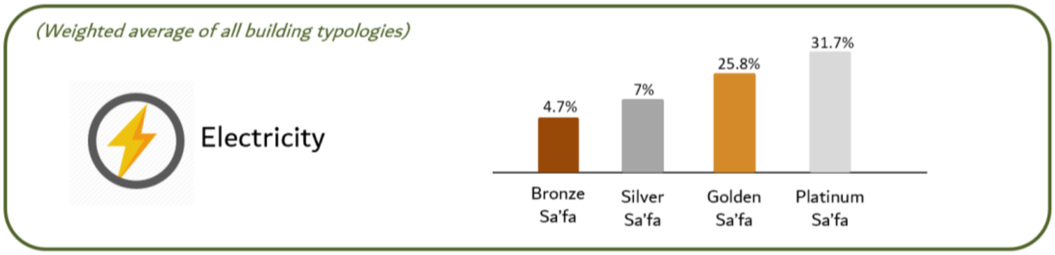


Figure 3: Electricity savings of Sa'fat evaluation system categories, (Zid 2018)

1.4 Research motivation

The main motivation and interest in this field of research is the shift in introducing intelligent systems globally. However, most of these strategies are implemented during the design stage of the building whereas existing buildings are still consuming high levels of energy without considering the development of their external envelop.

Moreover, there is a significant gap in the literature to define the approach that can be used to improve the performance of the building in terms of implementing kinetic systems on existing building when there are more than 500 examples of adaptive buildings. Nevertheless, adopting kinetic facades strategies is still not as common as expected even when research and actual studies have proved its advantages in enhancing the building performance and thermal comfort.

On the other hand, it is essential to introduce kinetic systems in hot climates as the façade should act as a moderator and should be more flexible to change its envelope in reference to the outer environment. The façade role should also be more active and not only saves energy but also helps in generating energy as it is considered a primary component in the building.

In addition, the development of Safat Dubai Green Building Evaluation system and the requirement of environmental tools that can be used to test kinetic systems in corporation with Dubai Municipality is one of the main motivations to explore the use of simulation tools such as IES VE software that would act as certified software for testing innovative technologies.

1.5 Research hypothesis

There is a direct relationship between adopting kinetic systems that respond to the outer environment and enhancing the energy performance of the building. Moreover, kinetic facades are designed in respect to their energy performance, thermal performance, daylighting levels and aesthetic values. However, in this research, it is hypothesized that:

- Kinetic façade systems achieve the targeted energy savings that was resulted from previous case studies while maintaining the proposed architectural concepts and preserving the functionality of the building.
- The impact of WWR on the building energy performance levels can be used as a design strategy for selecting the kinetic behaviour of the building.

1.6 Research objectives

The main objectives of this study can be summarized as follows:

1. To understand the main parameters of kinetic design principles and help in creating efficient, applicable and creative adaptive systems.
2. To provide a design strategy and methodological framework that response to three parameters; energy levels, cooling loads in reference to WWR analysis, sun exposure and the functionality of the building.
3. To introduce a new concept of shading systems by changing the façade traditional role to an active role in enhancing the energy performance of the building.
4. To modify the design through cumulative design process in reference to the main parameters of kinetic design principles
5. To propose an informative technology and kinetic architectural strategy at the same time
6. To validate onsite measurements of energy consumption and daylighting levels using simulation software, IES VE, in this research to be accredited for Dubai Green Building evaluation system (Sa'fat).
7. To test the impact of the proposed kinetic system on indoor daylight levels to avoid sun glare and solar gain in the building.

8. To compare between proposed adaptive kinetic façade and base case fixed shading system in terms of cooling demand and energy consumption.
9. To generate a design that act as an integral part of the building and the surrounding context and identify different scenarios that can be applied during the year for further assessment.
10. To investigate the enhancement of cost savings in terms of energy consumption for both electricity and cooling loads that can be achieved from kinetic system
11. To achieve a highly efficient building that is more flexible to adapt to the external environment.

1.7 Research focus and limitation

The research focuses on developing a kinetic system strategy selection framework focusing on environmental sustainability criteria. In addition, the framework will be validated on selected case study on an existing building in Dubai. This is considered the thesis novel contribution because it bridges the gaps between enhancing the performance of the building and preserving its architectural values as discussed in the design development of the proposed kinetic behaviour.

In addition, countries with similar climatic conditions will be able to use and implement the proposed framework for better survivability and profitability by saving energy and preventing unwanted sun glare and solar gain in the building to result in a better indoor environment. Further, by studying existing adaptive systems, the results will provide designers with different tools to measure the performance of the building.

Although solid to void ratio is one of the parameters used to assess the performance of kinetic systems, it will, in this research be treated as the main strategy for applying energy performance-based design and it will be used as the main factor for adjusting the openings of the proposed kinetic geometrics in a parametric model to select the behaviour of the proposed kinetic system in response to its thermal factors and architectural values. Mechanical systems, control equipment, structural analysis, fixation methods, and the depth of the kinetic system are excluded from the scope of this work.

The study has limitations that should be recognized when generalizing results due to the limitations of data collection and analysis, time and cost such as the depth required form the movement of kinetic surfaces and the ability to produce a laboratory prototype to conduct on site measurements of the proposed system.

As a summary of the limitations taken into consideration in this research, the following are considered:

1. Kinetic façade typology is limited to 3D geometric shapes that falls under automated movable screens typology.
2. The empirical data and case studies will be focused on the targeted energy savings of kinetic systems.
3. Data collection methods is limited to the existing energy bills for six months starting from May to October and on-site measurements for daylighting lux levels in the Mezzanine and the Viewing Bridge of Dubai Frame.
4. Cost analysis is limited to the savings in energy based on the current cost of each KW indicated in the energy bills.

1.8 Dissertation contents and structure

The dissertation consists of six chapters, listed below what is covered in these chapters;

Chapter 1, introduction, discusses a background information of kinetic systems and provides an overview of its status in a global and local level. Moreover, this chapter list the research motivation, research hypothesis, objectives, focus, and limitation.

Chapter 2, literature review, explains the definition of kinetic facades along with the history of kinetic façade development. Moreover, a comparison between fixed and kinetic shading is conducted to highlight the impact of kinetic façade on building performance. In this chapter, the factors that affect kinetic shading and kinetic shading typologies are illustrated with examples of kinetic shading applications. Further, kinetic façade design development is examined to include design stages, design strategies, evaluation strategies and implementation strategies.

Chapter 3, methodology, highlights the methodologies that are used to implement kinetic façade strategies to investigate the performance of kinetic systems where each one of them is explained to indicate its negative and positive features. The methodologies that will be discussed in this section consist of field experimental measurements, parametric tools, simulation tools and laboratories scaled prototypes that are used to get real life and efficient results. In addition, the methodological framework of this research methodology is described in this chapter.

Chapter 4, the case of Dubai Frame, introduces the case study selected for this research and describes the main features and the climatic profile of its area. Further, in this chapter a validation process is conducted to validate the use of IES VE software through site experiments and list the results obtained from the base case simulation.

In addition, chapter 4, discusses the design development of the proposed kinetic system through five stages; selecting the kinetic system, typology, mechanism, strategies and scenarios through a cumulative process that combine all the factors resulted from the proposed kinetic system strategies to generate an optimal design of the proposed kinetic behaviour.

Chapter 5, results and analysis, covers the results of the optimal kinetic system and compare the proposed nine scenarios that present the kinetic behaviour of the façade with the base case to generate an annual estimation of energy savings and cost analysis. Moreover, daylighting results is compared in the two selected areas (Mezzanine and Viewing Bridge) of each scenario to test the impact of kinetic systems on the selected case study indoor environment.

Chapter 6, conclusion, overviews a summary of the research where findings of the simulation results are discussed to answer the research hypothesis and to cross reference with the aims and objectives that is discussed in the introduction. In addition, this chapter identifies the contribution of the research and research limitations. Eventually, recommendations are identified for future studies.

CHAPTER TWO

LITERATURE REVIEW

Chapter 2 Literature review

2.1 Introduction

This chapter presents a review on relevant literature within the field of kinetic façade and adaptive systems to review the current state of art and highlight recent studies and research gaps.

This chapter is divided into eleven main sections. The first section discusses building envelopes and adaptive systems whereas the second section list the different definitions of kinetic facades. The third section discusses the history of kinetic façade and the development of adaptive systems at the present. After that, the fourth section highlights the difference between fixed and kinetic shading, more specifically within the performance of the building.

The fifth section discusses in details the impact of kinetic façade on building performance with an indicative figures and consumption levels. Further, the sixth section list the main factors affect shading performance which is primarily concerned within kinetic façade components.

The eighth section illustrates the typologies of kinetic shading that have been classified according to three different divisions; Structures, shapes and motion mechanisms and patterns that were divided to six categories from automated blinds, Egg-crate, optical panels, thermal change panels, fabric shading and automated movable screens. The ninth section gives an example of kinetic façade application according to these typologies.

The tenth section discusses kinetic façade design development with the key factors to help in designing kinetic façades, design stages, more specifically energy performance, daylighting control, thermal control and aesthetic based design. After that, evaluation and implementation strategies were highlighted to result in an efficient optimal design for adaptive systems. The main aim of this section is to discuss design as ill-structured problem and highlight the need of systemizing the design process in architecture field.

Eventually, in the eleventh section of this chapter, kinetic materials that can be used and selected while designing kinetic facades are identified with respect to its properties that affect the performance and movement mechanism of kinetic systems.

2.2 Building Envelopes and Adaptive Systems

Passive design strategies have an important role in designing sustainable buildings that respond to sunlight and heat such as building's shapes, orientation, materials, shades and blinds, (Sega Sufia Purnama & Sutanto 2018). However, shading strategies and adaptive systems have been mainly used in high-rise buildings. It is stated by Sharaidin & Salim (2012) that recently adaptive systems have been incorporated in buildings envelopes by architects and engineers to improve the performance of buildings and not only for their aesthesis values.

Bacha & Bourbia (2016) mentioned that the building envelop plays an important role in enhancing the performance of the building as it can reach up to 80% of an environmental solution to create a building that adapt with the surrounding conditions. Moreover, buildings envelop has become an essential resource of innovative research where adaptive systems were introduced to optimize the performance of buildings.

In addition, a study in California assessed the energy enhancement of buildings performance in response to their envelope position and found that dynamic shading and adaptive systems provide a better view quality with the required daylight factor and the lowest energy consumption, (Elzeyadi 2017).

Bacha & Bourbia (2016) indicated that Climate adaptive building shells (CABS) aim to provide an opportunity of reacting to solar radiation and to benefit from it to reduce the energy consumption of buildings in terms of cooling and lighting demand. Elzeyadi (2017) added that managing solar energy, light and air through a dynamic façade system by changing its geometry maximize the user comfort and enhance the performance of the building in relation to sun angles, daylight demands and outdoor climate.

The successful implementation of adaptive systems occurs during the summer months of hot humid and hot dry climates and regions. Moreover, shading strategies could achieve a big impact in mid-Western regions that have substantial cooling loads in summer, (Elzeyadi 2017). Sega Sufia Purnama & Sutanto (2018) indicated that the movement in relation to the sun direction minimizes the light but preserves the heat in the building and this can be achieved by converting a static envelop to an adaptive system.

Bacha & Bourbia (2016) added that adaptive systems allow the building envelop to be considered as a climatic moderator that has the ability to benefit from outdoor conditions by accepting or discarding the energy gained by the external environment. This results in reducing the artificial indoor energy requirement that achieve internal comfort for the occupants of the building.

It can be included that the amount of reduction in energy consumption depends on building envelope and shading strategies that control the behaviour of façade patterns in relation to climatic changes. Therefore, the use of adaptive systems through dynamic approaches and strategies is essential to achieve the optimal energy savings, (Elzeyadi 2017).

2.3 Kinetic façade definition

The concept of kinetic and responsive façade has been described in multi terminologies in the literature. However, they all stand to a specific way of response that can be defined as a kinetic response through the application of mechanical elements, movement mechanisms and materials, (Sharaidin 2014). The origin of the word kinetic as indicated by Alotaibi (2015) is Greek and refers to the behaviour caused by motion and the main aspect of integration to the surrounding environment and context.

Professor William Zuk in his book Kinetic Architecture in 1970, as cited by (Bacha & Bourbia 2016) and (Alotaibi 2015), described the kinetic term as a division in architecture where the building components or the building as a whole has the ability to adapt with the climatic variables through kinetics movements that can be incremental, adjustable, deformable and changeable through mobile modes.

The façade is defined as a building envelope that is used as a boundary to define indoor and outdoor spaces, (Sega Sufia Purnama & Sutanto 2018). On the other hand, Kinetic façade is the façade that is able to respond to the changes of the environmental conditions based on the functionality and the performance of the building, (Sharaidin 2014).

Nady (2017) defined kinetic façade as the façade that respond to the surrounding environment through typological changes of the building form or by the transformation of materials properties to enable the building to regulate its energy demand in relation to the surrounding climatic conditions.

In addition, Asefi & Shoaee (2018) indicated that the Kinetic façade is configurable system that is able to change its shape through movable joints partially or as an entire building in response to environmental condition to result in aesthetic values or to enhance the performance of the building. Moreover, Sega Sufia Purnama & Sutanto (2018) described the kinetic façade as a shade plane that react to different outside conditions, mainly implemented in high-rise buildings and react to solar movement and solar radiation intensity.

2.4 The history of kinetic façade development

In the past, traditional farmhouses used to save energy by keeping the heat generated from firewood through folding shutters as they used to create double skin façade effect and achieve a thermal barrier between the window and the shutter at night. Then, two layers of glazed windows used to be placed in each opening then manually, they used to open the exterior one in summer for ventilation purposes and keep them both closed in winter for higher insulation, (Nady 2017).

The history of kinetic architecture can be categorized in six intervals starting from initial designs and sketches and ending in high-tech techniques and systems of kinetic facades that we experience nowadays. Figure 4 describes the timeline of those intervals throughout the history, which will be discussed in further details below;

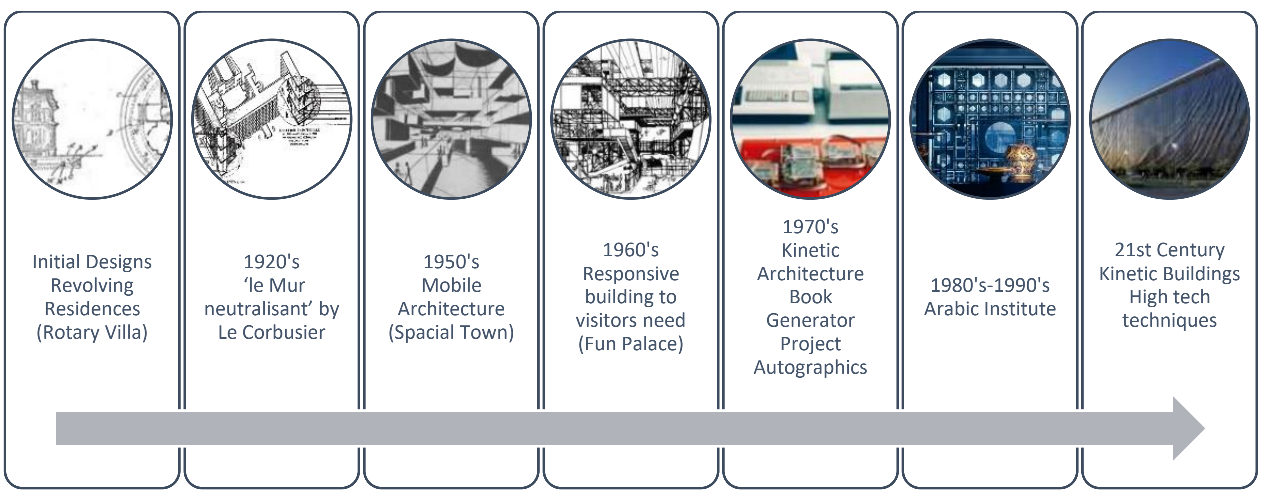


Figure 4: Kinetic Architecture timeline throughout the history, (Nashaat et al. 2018) (Nady 2017) (El-Zanfaly 2011) Edited

One of the early designs of kinetic architecture was a Rotary building that was designed and not built by Thomas Gaynor in 1908, (Nashaat et al. 2018). In 1916, the Corbusier has done an example ‘le Mur neutralisant’ when he managed to use stone and glass to a circuit of two membranes and managed to keep the temperature of 18 degrees in Moscow, (Nady 2017). After that, in 1935, Angelo Invernizzi has built a kinetic villa; Villa Girasole that follows the sun and rotates fully over three circular tracks, (Nashaat et al. 2018).

In 1950’s and 1960’s Mobile architecture was introduced when Yona Friedman questioned architect’s decisions of controlling the life of users inside their buildings and proposed town planning in 1959 where a town can be constructed in flexible architecture where people would have the ability to adjust their spaces the way they need it, (Nashaat et al. 2018).

On the other hand, in 1961, Cedric Price designed the Fun Palace where he created different spaces defined in movable units. In 1967, Richard Fuller used an adaptive envelope in US Pavilion in expo Montreal that is described in Figure 5 below, where the dome materials were created from a transparent acrylic sheets and steel structure that is controlled by the computer and designed to achieve thermal comfort within the pavilion, (Bacha & Bourbia 2016),(Sharaidin 2014) and (Nashaat et al. 2018).

Moreover, in the 1970’s, William Zuk discussed the systemic knowledge, essentials of kinetic architecture, active control devices and many other features in his book; Kinetic Architecture, (Bacha & Bourbia 2016),(Alotaibi 2015),(Nashaat et al. 2018). In addition, in 1976, Cedric Price has proposed The Generator Project where he developed a controlling processor that would help in creating intelligent buildings which respond to the use of the building. John Frazer, in 1979, has developed a company that took the generator a step forward to create the first microcomputer design in the world, (Nashaat et al. 2018).

Furthermore, in 1987, a major revolution in kinetic architecture was introduced by Jean Nouvel that is described in Figure 5, when he introduced a kinetic geometry of Arabic patterns in square bays in his design and created an innovative building, Arabic Institute in Paris, (Nashaat et al. 2018), (Meagher 2015).

The twenty first century was a start point in Kinetic architecture development. For example, in 2011, a kinetic wall for the parking of Brisbane Airport was constructed from 250,000 panels from aluminium that move with the wind. Moreover, Mercedes Benz stadium in Atlanta was designed to allow the roof to open as a camera aperture in a diagonal side to create an innovative design of retractable roofs, (Favoino 2018).

In addition, in 2008, a reinvention of Arabic screens was introduced in Al Bahar tower in Abu Dhabi where triangular panels were used as a shading mechanism controlled by an actuator that responds to the sun movement. Al Bahar tower managed to result in 50% reduction in energy consumption, increase the occupants' comfort and achieve the required indoor lighting levels. Figure 5 below describes the façade mechanism of the building, (Attia 2017) (Alotaibi 2015).

Recently, a frame movement mechanism was introduced by Kjeld Johnsen as he has developed an energy frame that act as a skeletal façade system that can be attached to the window frame. His proposed mechanism allows the frame to move vertically and horizontally to interact with the sunshade, ventilation, noise and lighting controls. On the other hand, Zoltan Nagy introduced BIPV in his façade that result in 25% of energy savings. He used a real façade prototype to conduct numerical calculations for a proper assessment of the proposed adaptive solar façade, (Sega Sufia Purnama & Sutanto 2018).

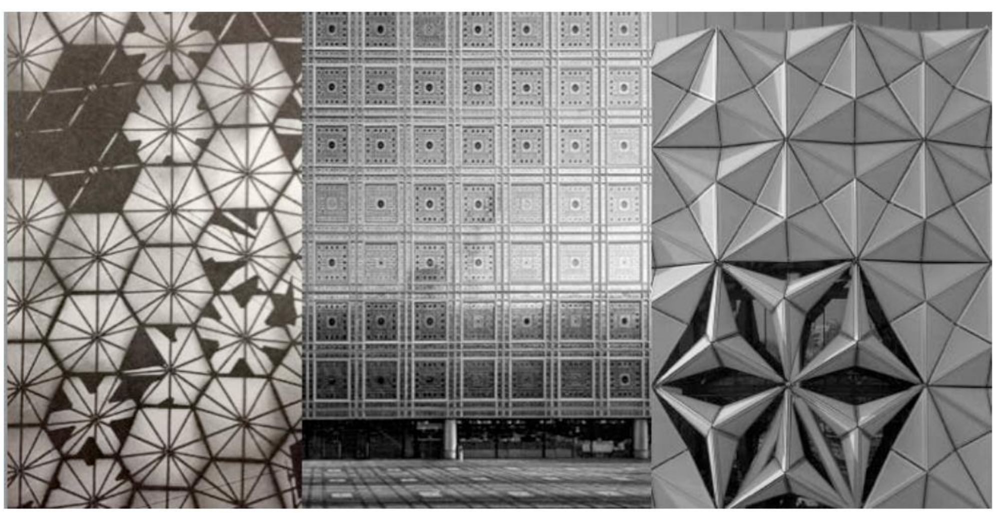


Figure 5: Expo67 US Pavilion, Arabic Institute, AlBahar Tower, (Sharaidin 2014).

2.5 Fixed and kinetic shading

The main difference between fixed and dynamic shading systems is the dynamic ability to adjust according to the surrounding environment where internal needs, indoor comfort and energy demand are maintained, (Elzeyadi 2017).

Norbert has questioned in his book; heating, cooling, lightening how static systems are used to respond to dynamic problems and has explained that the extensive use in energy in high rise buildings is a result of using static elements to respond to a natural condition that vary from time to another, (Sega Sufia Purnama & Sutanto 2018).

Several studies were defined by (Elzeyadi 2017) (Bacha & Bourbia 2016) to discuss the impact of dynamic shading in comparison to static shading which can be concluded in the results listed below and described in Figure 6.

1. Kinetic shading has a higher impact of daylight and a better quality of view for the lowest energy demand.
2. Static shading would lead to a slightly increment in heating loads in cold climates. However, kinetic shading that can be adjusted in relation to solar transmittance and improve the energy consumption of the building.
3. In terms of daylighting, kinetic shading would enhance the energy used by lighting from 5% to 11%.
4. In a study that used dimming strategy for both types of shading, kinetic louvers resulted in energy savings from 5-14%.
5. Daylight factor can be increased from 2% by 70-150% in kinetic louvers compared to static louvers.
6. Previous studies have shown a positive energy reduction in both office and commercial buildings.
7. Indoor Environmental Quality (IEQ) can be enhanced in buildings with kinetic shading.

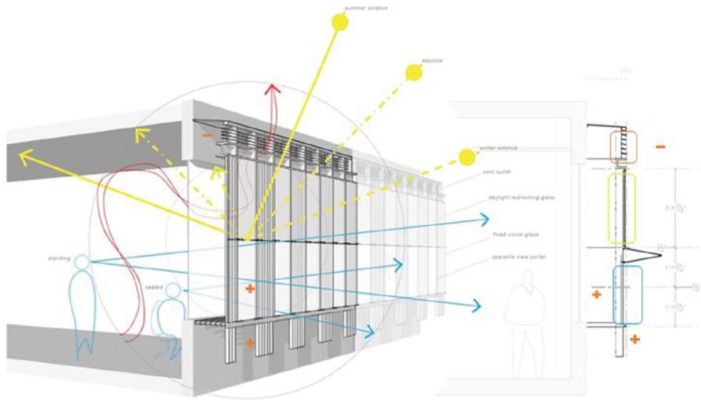


Figure 6: Kinetic ability to adapt through sun movement, view quality and thermal or optical processes, (Elzeyadi 2017).

Perino & Serra (2015) concluded that based on the results conducted from kinetic shading in comparison to traditional static facades, the modification of six dynamic properties of the building façade; density, materials thermal and heat conductivity, surface absorption coefficient and opaque transparent ratio and glazing typology would allow an improvement of 16-18% of building performance levels.

2.6 The impact of kinetic façade on building performance

The focus of kinetic façade from research and recent studies is energy saving. It is stated by Alotaibi (2015) that kinetic façade could make a reduction in energy consumption by 30% for cooling and heating in comparison to a building with no shading system.

Glazed façade is commonly used in office buildings due to its luxurious appearance. However, as described by Bacha & Bourbia (2016) that this result in high energy consumption as the façade consume approximately 25% of the building energy demand due to both cooling and heating. Therefore, Elzeyadi (2017) stated that solar shading would achieve up to 13.75% energy saving in all climate zones with high solar impact, Figure 7 describes the relation between shading strategies and indoor comfort in all climate zones.

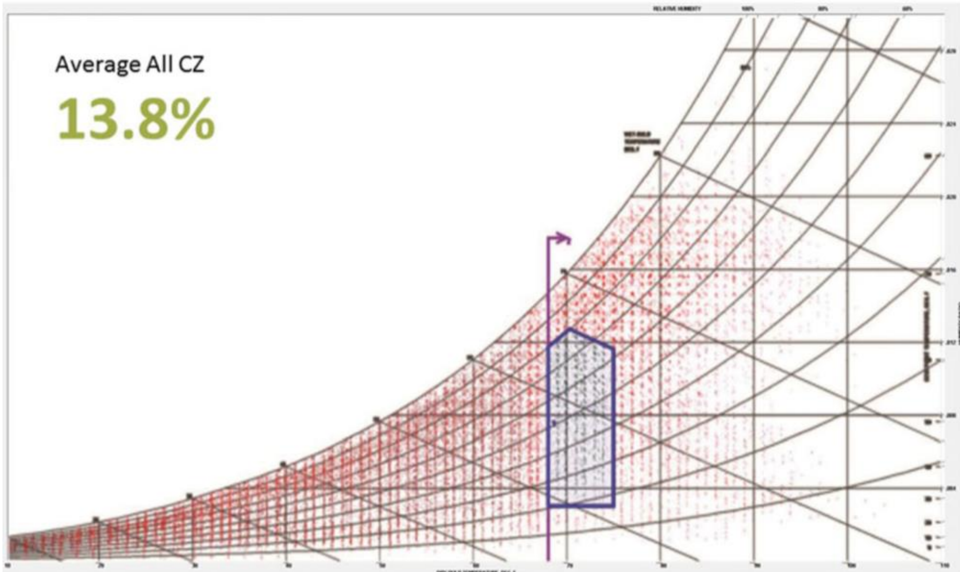


Figure 7: Indoor comfort and shading strategies in all climate zones, (Elzeyadi 2017).

According to Johnsen & Winther (2015), a study conducted on an office building in Denmark managed to enhance the building performance by lowering the total energy consumption of the building from 50 kwh/m2 to 25 kwh/m2 while using smart control systems by reducing the transmission heat losses, increasing daylight utilization and time for natural ventilation, controlling solar gain and controlling the miscellaneous energy.

Sharaidin & Salim (2012) mentioned that kinetic shading contributes in a significant reduction in energy consumption that would reach up to 43% whereas the reduction in indoor air temperature would range from 4.0 C° to 4.8 C°. Sega Sufia Purnama & Sutanto (2018) added that cooling loads of a South facing office in Athens would be reduced by 9.8% compared to static façade. On the other hand, Wagdy et al. (2015) investigated the implementation of Hybrid double facades and managed to contribute in 23% energy savings.

In addition, a study conducted by Ahmed et al. (2016), for a kinetic Aluminum window frame led to 18-20% of energy savings compared to a building with no shading system. Furthermore, Hansanuwat (2010) assessed different configurations of kinetic louvers and resulted in 28% to 30% energy reduction for heating and 28% to 33% for cooling.

Marysse (2016) concluded that implementing kinetic strategies would achieve a possibility of energy savings between 10% -15% by reducing the use of HVAC systems once internal thermal comfort and relative humidity levels are sufficient to satisfy the users of the building. Furthermore, a reduction of operational cost due to lower use of HVAC and artificial lighting would range from 10% to 40%.

2.7 Factors affect kinetic systems performance

There are several factors and parameters that should be taken into consideration while designing kinetic facades, each one of them has a potential to affect the overall performance and perception of the building. Recent studies have measured the performance of adaptive systems in reference to the following parameters, (Romano et al. 2018) (Nady 2017).

1. Materials: the use of high innovative materials help in absorbing solar energy such as PCM, TIM, BIPV, ETFE, etc. Moreover, the innovative technologies of materials have a significant effect on the comfort of the building.
2. Natural Ventilation: control devices and mechanical ventilation systems manage natural ventilation within the building and is able to direct fresh air within the building. Moreover, ventilation strategies that can be adopted in building's skin play significant role of air exchange. For example, louvers would allow the circulation of local air whether it was simple, repetitive or small louvers.
3. Sun control: light control devices measure the amount of light that enters the building, which affects indoor temperature and thermal comfort. For example, blinds are considered a simple way to control the sunlight admitted to the building while maintaining its overall appearance.
4. Daylighting: adaptive systems would enhance the use of natural daylighting and reduce artificial lighting. For example, movable light shelves would be a simple feature and take advantage of reflectivity and reflect light in to the space.
5. Thermal insulation: thermal insulation can be adopted by using high insulated material and double skin façade that would reduce heat losses and enhance the thermal performance of the building.

6. Moisture control: control devices such as Bitumen that consist of Hydrocarbons would act as a moisture barrier in buildings that would prevent condensation and unwanted rain entering the building.
7. Structural efficiency: the integration of structural elements with the building façade especially in high rise construction helps in defining the character of the building.
8. Mobile screens: the movement of mobile screens provide control on solar radiation.
9. Technological solution: technology used to control indoor comfort inside the building.
10. Automation systems: building management systems that manage building skin and plants.
11. Energy generation: building façade would become an energy source if it was integrated with photovoltaic, thin films to act as a shading device and generate power to the building.

2.8 Kinetic shading typologies

Adaptive façade can take many configurations and shapes. It is stated by Bacha & Bourbia (2016) that adaptive systems contain internal and external systems with different types of shutters and blinds which can be converted to innovative systems and kinetic mechanisms. Recent studies have classified Kinetic systems according to three different divisions; Structures, shapes and motion mechanisms. In this section, the typologies of kinetic shading systems will be discussed in reference to those divisions, (Bacha & Bourbia 2016) (Nashaat et al. 2018) (El-Zanfaly 2011) (Elzeyadi 2017) (Marysse 2016).

Kinetic structures were classified by Michael Fox to three typologies. The first one is Deployable kinetic structure that would be located in temporary locations and would be applied in pavilions and self-assembling structures where it can be easily transferred. The second typology is embedded kinetic structure where it is fixed in building or an architectural system in response to environmental or human factors through flexural, torsion, vibration and many other kinetic movements. The third typology is Dynamic kinetic structure, which is dependent and include multi modular component such as louvers, partitions, ceilings, walls and doors, (El-Zanfaly 2011), (Fox & Kemp 2009).

In addition, kinetic structures were classified by Mazier Asefi in two types based on the movement of transformable structures. The first type is transformable tensile structure that consist of tensile membranes and compressive tensile structures. The second type is transformable structures that are bended and compressed through bar and frame structures, (El-Zanfaly 2011). Figure 8 indicates Mazier Asefi classifications of architectural transformable structures in more details.

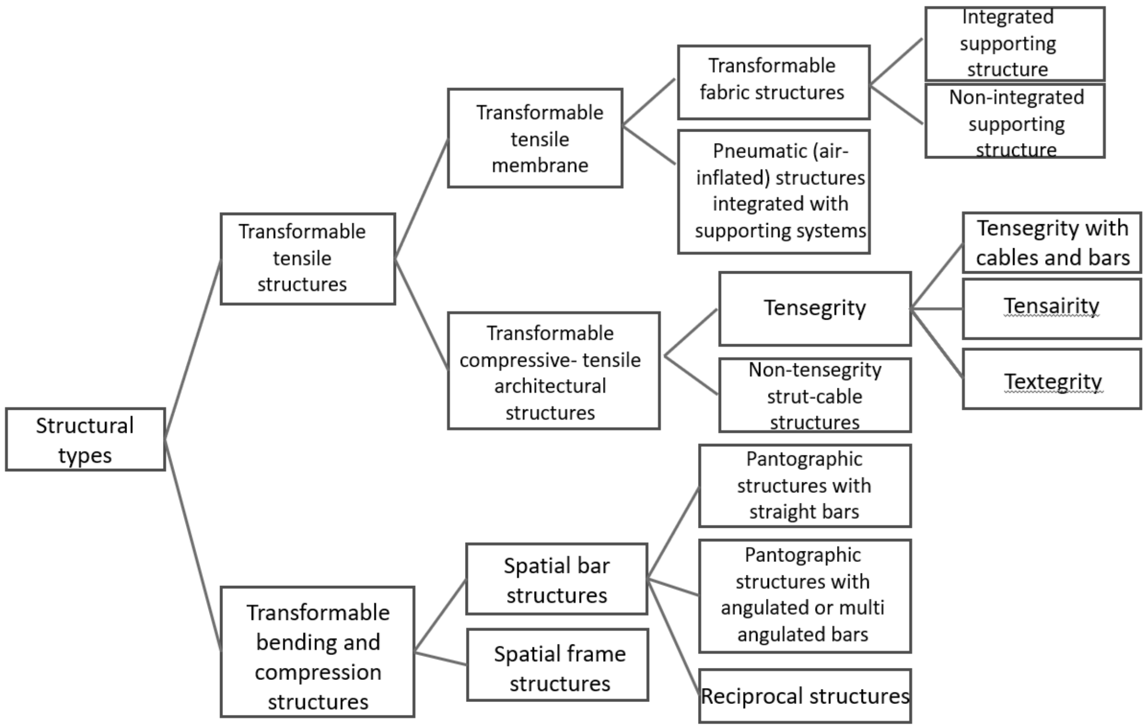


Figure 8: Mazier Asefi classifications of architectural transformable structures, edited, (El-Zanfaly 2011).

William Zuk in his book, kinetic architecture, has classified kinetic architecture in eight classes and called them “Kinetiscism”. The first four classes were defined as close systems where the design strategies should be made prior the selection of the original four. Those Kinetiscism are; self-erecting structures, static structure that is controlled kinetically, kinetic component and reversible architecture, (El-Zanfaly 2011) & (Zuk & Clark 1970).

Nashaat et al. (2018) has introduced the applications of kinetic architecture into three categories starting from kinetic structure systems, then kinetic interiors and ending in kinetic facades. In those configurations, kinetic façade was classified into four main categories based on its geometric transaction and movement mechanism; translation, rotation, scaling and material deformation that can be described in Figure 9.

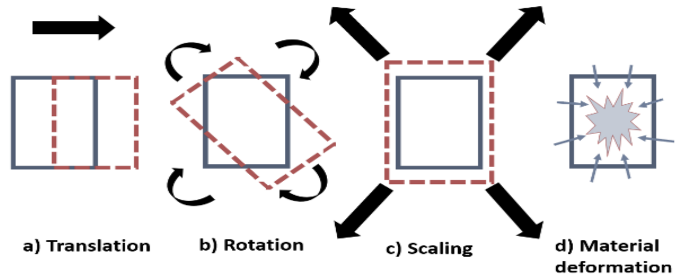


Figure 9: Kinetic façade geometric transitions forms, edited, (Nashaat et al. 2018)

On the other hand, Michael Schumacher has classified the motion of kinetic structures in his book Move: Architecture in motion- dynamic components and elements into movement mechanisms; swivel, flap, pneumatic, rotate, slide, expand, fold ad gather (roll up), (El-Zanfaly 2011).

Elzeyadi (2017) has classified shading systems based on the shape of the kinetic system to six typologies; automated blinds, egg crates, optical panels, thermal change planes, stretched fabrics and automated movable screens, which are presented in Figure 10. In this study, he managed to assess their impact on energy consumption, glare and daylight control for an office unit in Climate Zone 4C in ASHRAE. The following sections discuss those typologies in detail with some applications of existing buildings that has similar types of shading systems.

Automated blinds | Egg Crate | Optical panels | Thermal change planes | Fabric/ Weave | Automated Movable Screens

Figure 10: Shading typologies, (Elzeyadi 2017)

2.8.1 Automated blinds

Automated blinds systems improve thermal and visual comfort and enhance the energy demand of the building by providing additional dynamic comfort in comparison to static blinds systems. Statics that define the improvement of the building performance and indoor comfort can be listed as follows:

1. Automated blinds provide 12% savings for artificial lightings and balance between the thermal performance and daylighting.
2. DGI values were enhanced to acceptable levels instead of uncomfortable levels.
3. sDA (300) percentage was increased from 36% to 52%.
4. Minimizing heat gain and sun glare while maximizing daylight distribution and outdoor views during summer

2.8.2 Dynamic Egg Crates

Dynamic Egg Crates is a combination of vertical and horizontal shades through movable fins that is placed in grid formation and geometric configuration. The aim of this combination is to protect the building from both horizontal and vertical sun angles. The statistical data below defines the enhancement of building envelopes that was determined through previous studies of Egg-Crates shading systems.

1. Egg crates provide the best enhancement when it is placed in Eastern and Western orientations and in hot and dry climates.
2. Save energy from 20% to 38.5% for commercial buildings
3. Save energy from 8.9% to 20% in cooling seasons
4. Additional savings were higher when it was combined with external louvers.

2.8.3 Holographic optical elements (HOE)

Optical dynamic shading consists of variety of films, reflection and refraction mechanisms for heat and light, coatings and different materials. Those elements help in managing glare and maintain daylighting levels while controlling the direct solar radiation. A study of HOE for a high-rise building in a hot arid climate showed the following:

1. Cooling loads were reduced by 30% in comparison to fixed external blinds.
2. HOE manages to reflect the incident radiation and allow diffuse light to pass through.
3. HOE act as a movable layer that lies in between double-glazed windows and maintain windows view unobstructed.

2.8.4 Thermal change planes

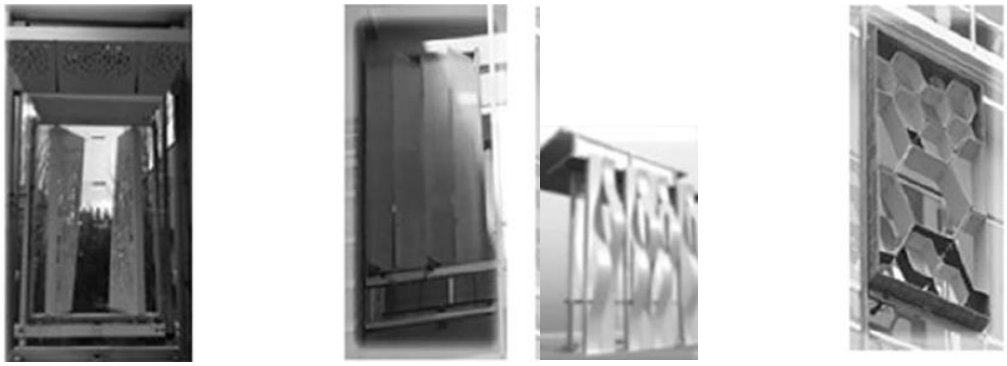
Thermal panels have similar characteristics of optical shades in which it employs variety of mechanisms, coatings and material changes. Those planes manage to control the direct radiation and glare to increase the penetration of daylighting deeper into the space.

2.8.5 Stretched fabrics

Stretched fabrics are usually projected from the building. However, fabric systems have less impact in managing glare and the of energy savings along with optical and horizontal blinds systems. In contrast, fabric elements need to be combined with hybrid structures that are considered as deployable compressive elements and have a subcategory of pneumatic structures that would be easily damaged. On the other hand, this typology would have better impact for wind and water as it can have breathable properties.

2.8.6 Automated movable screens

Automated movable screens can be divided to three types; deep planer screens, 3D paramedic screen and 3D geometric screens that are described in Figure 11. Solar screens have been implemented in hot dry climates, mainly in Egypt and Morocco to reduce cooling loads and mitigate overheating. This type of screens is related to the architecture of Middle East and North America such as Mashrabiyas, Gus walls and Jali screens.



Deep Screens | 3D Paramedic Screens | 3D Geometric Screens

Figure 11: Types of Automated Movable Screens, (Elzeyadi 2017)

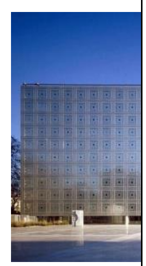
The efficiency of automated screens depends on the screen pattern, geometry, depth, solid to void ratio, operability, movement ability and the material. Statics has shown many advantages of automated screens that can be summarised as follows:

1. Automated screens result in 2% to 38% energy savings and improve indoor comfort in contemporary buildings.
2. A study resulted in 30% annual energy reduction in an automated screen that has 80% perforation for West and South façade and has a depth/opening ratio of 1:1.
3. Shallower screens have shown less impact on reducing heat gains in cooling season but managed to result in energy reduction.
4. Daylighting has lower levels in rounded screens with large diameters and is also connected to openings ratios to the panel solid parts.
5. To balance and optimise daylight penetration and energy savings, a ratio of 1:1 of depth/width of dynamic automated screens should be maintained.

2.9 Kinetic facade applications

There are many iconic buildings with innovative kinetic façade strategies. A brief of kinetic façade applications and case studies will be discussed in this section by indicating the main features of their kinetic strategies with an indicator of the building performance and the reduction in energy consumption. The following case studies and applications are listed in reference to the typologies of kinetic façade shading systems that was discussed in the previous section. Table 1 illustrates the case studies selected for each typology.

Table 1: Kinetic façade applications and typologies, edited, (Elzeyadi 2017)

Typology	Blinds	Eggcrate	Optical panels	Thermal change panels	Fabric/ weave	Automated Movable screens		
						3D Paramedic	Geometry	Deep Screens
Case Study								
	Council House 2 - Melbourne	Kiefer Technic Showroom - Austria	Gherkin Tower- London	Saint-Gobain - North America Headquarters	Burton Barr Central Library- Arizona USA	Thematic pavilion Expo 2012- Yeosu, South Korea	Arabic Institute- Paris	Kolding campus- Denmark

Council House 2 (CH2) is an example of automated movable screens under deep screen typology. It is an office building located in Australia that was awarded in a six Green star rating based on GBC of Australia rating system. The building comprises many innovative sustainable strategies such as chilled ceiling, roof turbines and kinetic timber shutters. Kinetic timber shutters protect the occupant from direct sun by a kinetic device that track the sun path and provide full shading in summer. Moreover, the screens improved staff productivity by 10.9% with 85% reduction in electricity consumption, (Alotaibi 2015). Figure 12 illustrates some images of CH2.

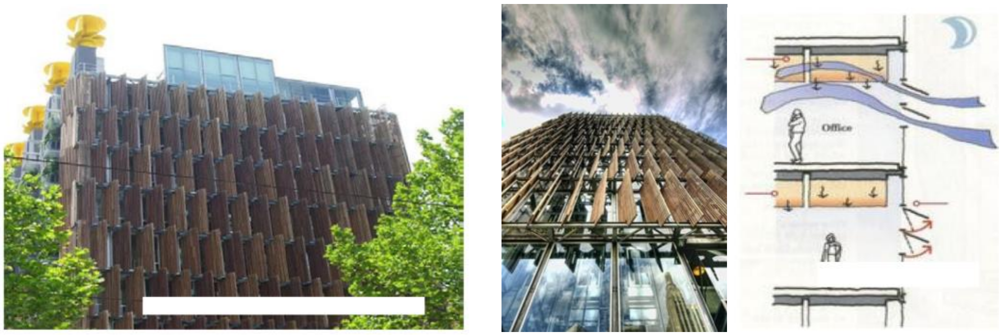


Figure 12: CH2 Kinetic Timber Façade and movement mechanism, (Alotaibi 2015)

Kiefer Technic Showroom is an example of Eggcrate shading typology. The showroom is located in Austria with a kinetic façade that works through electric controls that can be adjusted through the occupants of the building. The user would be able to change the panels' angles and the amount of light admitted to the building interiors, (Elzeyadi 2017) (Nady 2017). Figure 13 demonstrates the movement mechanism of the showroom shading panels.

Figure 13: Kiefer Technic Showroom- Austria, (Elzeyadi 2017) (Nady 2017) (DYNAMIC FACADES: THE STORY 2019)

Gherkin Tower is one of the iconic buildings that are located in London; its shading typology is an example of optical shading that is described in Figure 14. The façade is designed with an advanced glazing technology that allows the building result in 85% solar protection through ventilated cavities and computer- controlled blinds. Furthermore, the building has weather sensors that monitor solar levels, temperature, wind speed and adjust blinds opening to achieve an overall energy saving of that would reach up to 50%, (Elzeyadi 2017) ("30 St' Mary Axe (The Gherkin), London | Archinomy" 2019) (Raoa 2014).

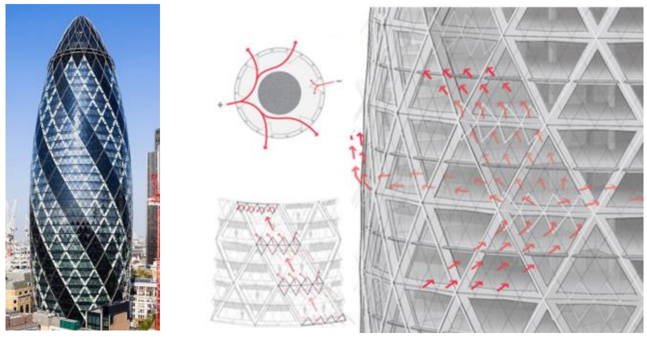


Figure 14: Gherkin Tower- London, (Elzeyadi 2017) ("30 St' Mary Axe (The Gherkin), London | Archinomy" 2019) (Raoa 2014).

Saint-Gobain headquarters is an example of thermal change panel’s typology of kinetic shading, which is located in North America. The building was redeveloped to an advanced office building instead of two existing 1960’s buildings and was given the certificate of LEED platinum. The aim of this project is not only to create a dynamic space but also to provide a living showroom for a dynamic thermal glass panel that is described in the Figure 15. The façade consists of electrochromic glass that manages to adjust the room temperature by 10 to 12 degrees in summer and increases it in winter at a touch of an iPad, (Elzeyadi 2017) (Winstanley 2019).

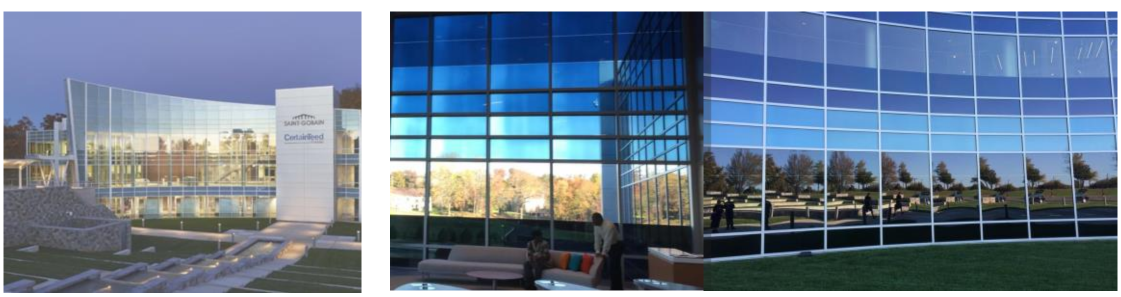


Figure 15: Saint-Gobain North America Headquarter, (Elzeyadi 2017) (Winstanley 2019).

Burton Bar central library is an example of fabric/ weave shading system that is located in Arizona, USA. The North elevation of the library has an innovative system of shading sails that protect the building from solar gains and glare while providing an optimum view for the users of the building. On the other hand, the South elevation has automated louvers that have an automated tracking device which respond to sun angles. The building results in one-third reduction in the building energy demand that was assumed by utility experts. Figure 16 shows some images of the building shading typology, (Elzeyadi 2017) (Kostelni 2015).

Figure 16: Burton Barr Central Library- Arizona USA, (Elzeyadi 2017) (Kostelni 2015).

An example of Automated Movable screens, 3D Paramedic typology is the thematic pavilion of Expo 2012 in Yeosu, South Korea as shown in Figure 17. The façade consists of 108 kinetic GFRP louvers, fixed from the top and the bottom with an actuator from one edge of each panel. The actuator manages to push the edges to create an elastic movement and result in rotating the GFRP panels. This kinetic system generates energy by converting the elastic energy stored in the panels into electrical power, (JUNGJOHANN et al. 2012) (Barozzi et al. 2016).

Figure 17: Thematic pavilion of Expo 2012 in Yeosu, South Korea, (JUNGJOHANN et al. 2012) (Barozzi et al. 2016).

Arabic institute is one of the iconic buildings of Jean Novel that was built in 1980's. The building façade is classified as a geometric automated façade that was inspired by the Mashrabiya. The façade is operated through mechanical actuators and sensors that respond to the intensity of sunlight and reduce the sun exposure to the building to allow the daylight to suffuse the interiors. This building played a significant cultural and aesthetic role in the design of kinetic architectural facades, (Meagher 2015) (El-Zanfaly 2011).Figure 18 describes some images of Arabic Institute in Paris.

Figure 18: Arabic Institute- Paris, (Meagher 2015) (El-Zanfaly 2011).

Kolding campus is an example of deep screens automated façade which is located in soother Denmark. The building consists of perforated triangular dynamic solar shading that adjust based on the desired daylight levels. The automated screens are fitted with sensors that measures both light and heat levels to mechanically regulate the movement mechanism of the perforated shutters through a small motor. The aim of the building is to achieve 50% reduction in energy savings and reach annual energy consumption to 36 kwH/m2/year. Figure 19 presents some images of the kinetic movement of Kolding campus façade, ("SDU Campus Kolding / Henning Larsen Architects" 2015) (Aelenei et al. 2018).

Figure 19: Kolding campus- Denmark

2.10 Kinetic façade design development

Designing Kinetic façade is considered a design of process not artifact. This process includes creating and evaluating different elements of kinetic façades while considering the façade materials, patterns and mechanisms in responding to the surrounding conditions.

Sharaidin (2014) pointed that the involvement of kinetic elements within 3D physical components makes designing responsive façade a complex task. Therefore, further details of kinetic façade design development will be discussed in this section by indicating the key elements that help in designing kinetic facades, kinetic façade design stages, design evaluation and implementation strategies.

2.10.1 The main parameters to help in designing kinetic façade

For designing kinetic facades and before reviewing design stages, strategies, evaluating and testing kinetic facades, it is fundamental to characterise the parameters that affect the efficiency of adaptive systems.

According to (Aelenei & Vieira 2016), a summary of adaptive systems key elements and parameters were discussed in reference to the scientific plan of COST TU1403 as represented in Figure 20. The purpose of adopting kinetic system was listed as the main key element of kinetic façade characterisation parameters followed by the responsive function, operation, materials and systems components, response time, spatial scale, visibility and the degree of adaptability.

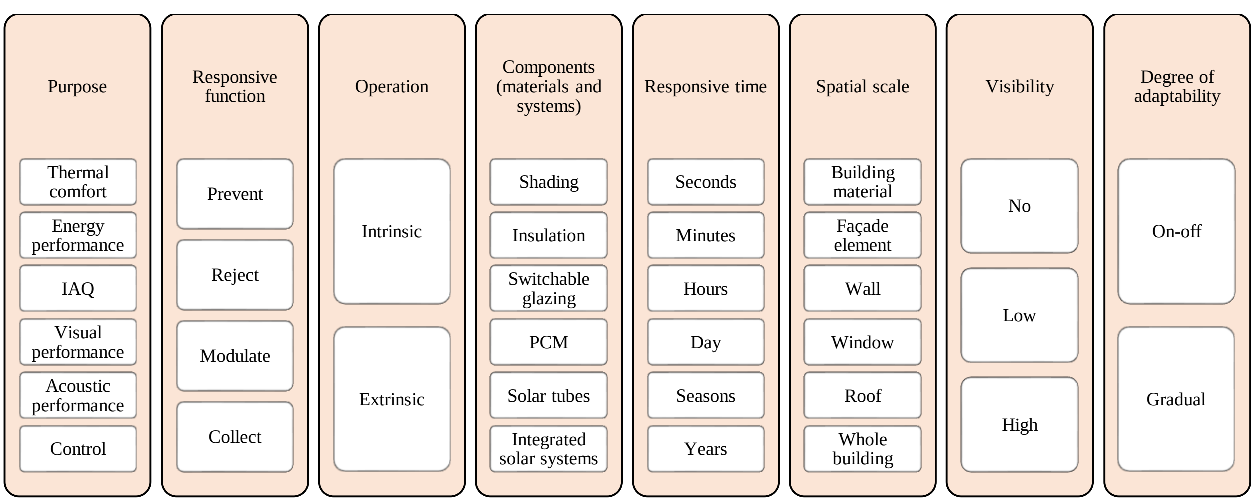


Figure 20: overview of the elements to help in designing kinetic façade, (Aelenei & Vieira 2016).

Nady (2017) added that the main parameters and design elements of kinetic facades include and not limited to building orientation, position and materials, shading devises, windows type and location and roof shapes. Therefore, the selection of the façade should be considered as a major task during the design process of the building. Sharaidin (2014) agreed by indicating that the design decisions of kinetic façade are associated with kinetic mechanism and components to ensure the effectiveness of the façade operation.

On the other hand, external factors need to be taken into consideration while designing kinetic façade such as solar radiation that addresses visual and thermal comfort, outdoor temperature and humidity, wind and precipitation including natural ventilation and outdoor noise of the building. These factors affect the performance of the façade and the human comfort, which need to be considered in the façade design, (Aelenei & Vieira 2016) (Johnsen & Winther 2015).

An analysis conducted on 130 building to measure the global distribution of external factors found that solar radiation and temperature accounted for the highest external factors that affect the design of the buildings with 82% for solar radiation and 76% temperature as indicated in Figure 21, (Aelenei & Vieira 2016). Furthermore, Nady (2017) highlighted that most researchers and studies focus on thermal comfort aspects to be able to create acceptable indoor environment.

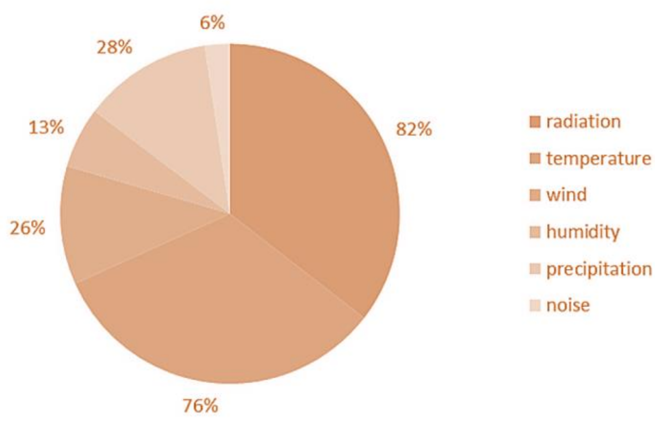


Figure 21: Kinetic facades external factors global distribution, edited, (Aelenei & Vieira 2016).

2.10.2 Design stages

At early design stage, the performance of kinetic design should be evaluated and examined in response to the required role of the building façade configurations. Sharaidin (2014) mentioned that this will help designers to understand the strategies in developing the kinetic façade. Therefore, early design decisions should take into consideration the design system, energy performance, movement mechanism, construction methodology, materials and the consultant experience.

Sharaidin & Salim (2012) Discussed Kinetic façade design stages and mentioned that designing kinetic facades should start with design sketches and followed with digital simulation that validate and define the performance and the required measures of the proposed façade in real conditions. After that, a physical model prototype would be required for on-site experiments and measurements prior installing the proposed façade.

2.10.3 Design strategies

Recent studies have highlighted many design strategies for designing kinetic facades. In this section, a summary of how to integrate kinetic facades through new design approaches for content and physical integration will be discussed with an indication of some examples were used to formulate the proposed design strategies as shown in Figure 22.

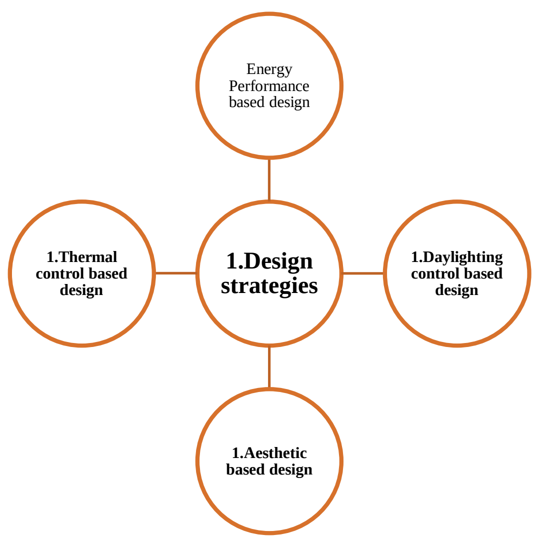


Figure 22: Kinetic façade design strategies

2.10.3.1 Energy Performance based design

Designing kinetic facades for energy performance is the main interest for designers and architects for conducting an effective design of kinetic facades. Current approaches use digital tools and generative principles to provide digital models that have the ability to manipulate geometric properties on the basis of performance analysis.

A study conducted by Sharaidin & Salim (2012), investigated the working mechanism of kinetic façade relating performance environmental simulation by using parametric design modelling that achieve the optimum performance of the building. Figure 23 describes the patterns generated from the simulation results according to kinetic performance in relation to daylight levels. Similar simulation models were adopted in Aedas, Abu Dhabi and TIC building in Barcelona.

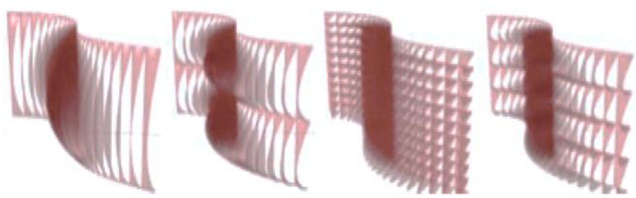


Figure 23: Kinetic patterns of different generative models according to kinetic performance, (Sharaidin & Salim 2012).

In addition, Nady (2017) added that the building that is designed to have energy conscious façade should be constructed with strength and stability, control of heat, durable, control of air and vapour, fire resistance and cost effective. This can be illustrated through Kolding campus where the energy performance of the building was connected the change of heat and light.

It should be noted that in the literature, designers have established their own design strategies while designing kinetic facades due to the need of generating new design approaches to result in a better design application that achieve the required building performance, (Sharaidin 2014).

2.10.3.2 Daylighting control-based design

Daylight control-based design is appropriate for all design conditions. It is indicated by Nady (2017), that Arab institute in Paris is a notable example on daylight control where circular shutters operated as camera lenses that control the penetration of solar radiation by widening and shrinking through sensors and actuators that respond to daylighting as indicated in Figure 24.

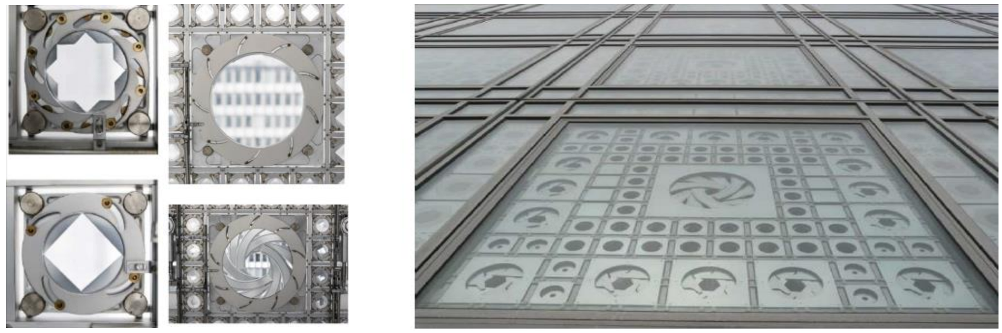


Figure 24: Arabic Institute daylighting control base design, (Nady 2017)

Kinetic façade can be linked by daylight simulation tools where plugins can be connected to perform daylight analysis according to daylight standards such as LEED on an existing architectural model. Those parameters can be connected to the rotation, size and opening of kinetic geometrics to determine the optimum configuration that suit the space. A study conducted by Elghazi et al. (2014), adopted this strategy for a living room located in Cairo in a hot arid climate where a Kaleidocycle skin was modelled for daylight analysis as described in Figure 25.

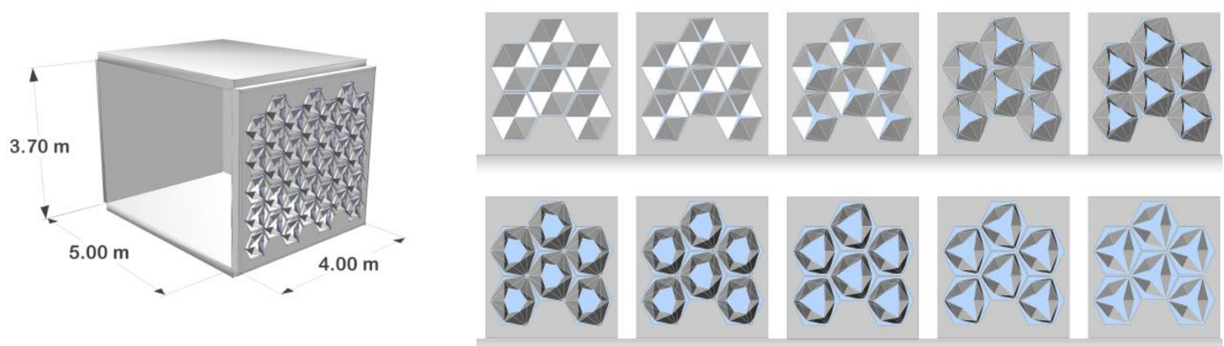


Figure 25: Kaleidocycle skin modelled for a South facing living room in relation to daylight analysis with their rotation angles, (Elghazi et al. 2014)

Loonen et al. (2013) highlighted that changing the direct effect of kinetic materials is concerned with material's light transmittance properties where smart elements are able to adjust their optical properties to modulate daylight levels and solar energy. Therefore, successful implementation and operation of kinetic façade is a result of effective control of their behaviour.

2.10.3.3 Thermal control-based design

Managing heat fluxes and minimizing transmission losses is the aim of thermal control-based design. P. Jekot (2008) mentioned that sun radiation should be adapted through developed devices to result in efficient designs whereas protecting and filtering layers, sun breakers, louvers and any other kinetic shading can be designed to control solar radiation while maintaining the visual contact with the exterior.

A study of kinetic shading was adopted in a high rise building in Jakarta, to overcome the heat radiation and transfer in a tropical area. The study was divided to different stages, for designing the façade, a shadow simulation of static shading was done through simulation software, and then kinetic façade was developed in reference to the shadow provided from sun movement. Figure 26 describes the process that was adopted in this study to design kinetic façade where the effectiveness of shading was measured based on the percentage of the shadowed area, (Sega Sufia Purnama & Sutanto 2018).

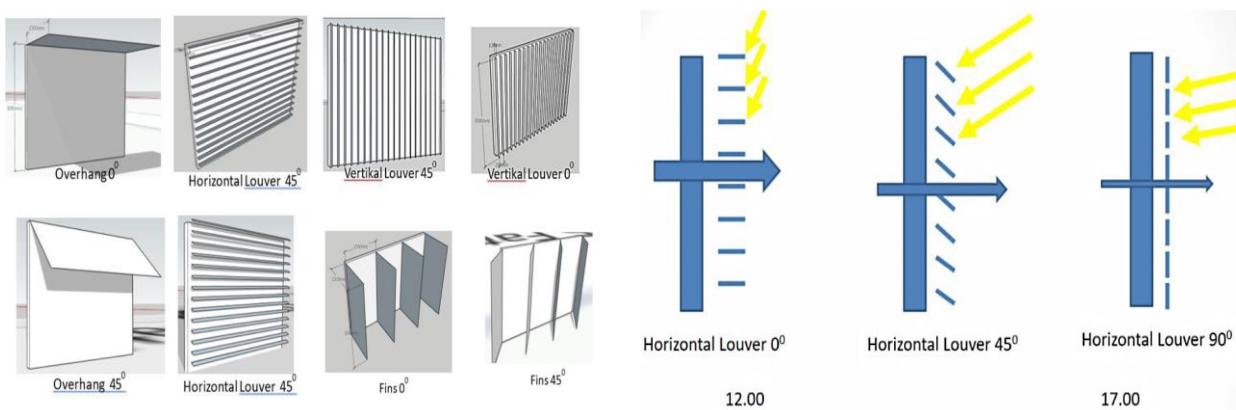


Figure 26: The process of kinetic façade development for shadowing, (Sega Sufia Purnama & Sutanto 2018).

Bacha & Bourbia (2016) concluded that designing kinetic facades to achieve thermal comfort and the required daylighting levels can be integrated together whether it is controlled by the users or the computer or even based on a natural reaction as it is important to consider the heat gain and the light admitted to the building to respond to solar radiation.

2.10.3.4 Aesthetic based design

Designing kinetic facades for their aesthetic values was explored by architects and designers who took their inspiration from geometric shapes, origami and nature. Elghazi et al. (2014) expresses how origami patterns were explored through paper folding techniques based on shape, sequence and the relationship of geometric rules and folding morphology that can be described in Figure 27

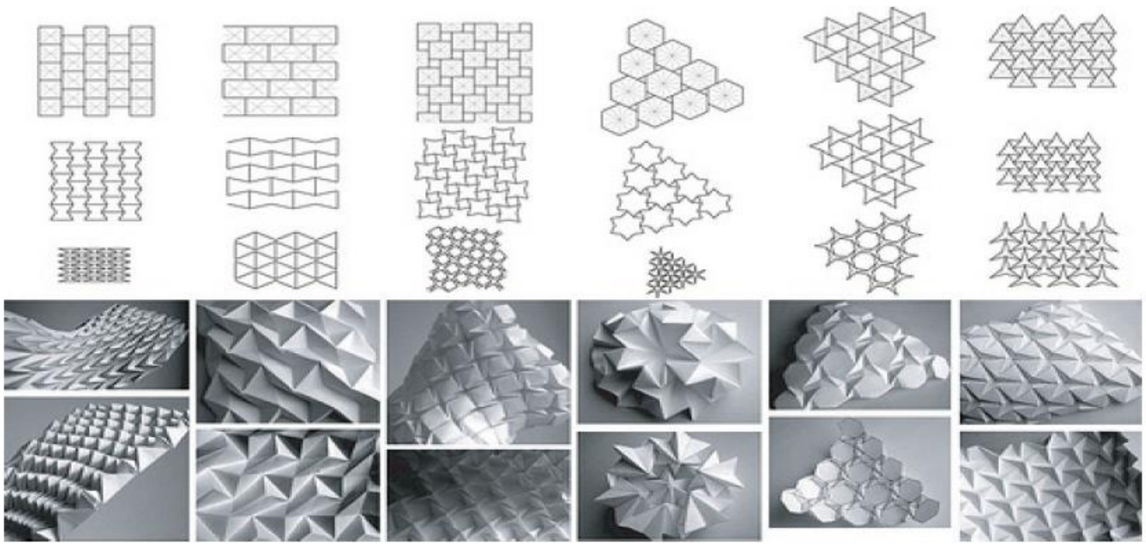


Figure 27: Origami forms that can translated to parametric models, (Elghazi et al. 2014).

In addition, aesthetic values can be implemented using adaptive decorative structures such as Pantographic, which looks like scissors elements where modules can be transferred to different configurations and patterns to create 2D and 3D geometries in the design of the system. Figure 28 describes the movement of Pantographic decorative structure that act as a kinetic façade, (Asefi & Shoaee 2018).

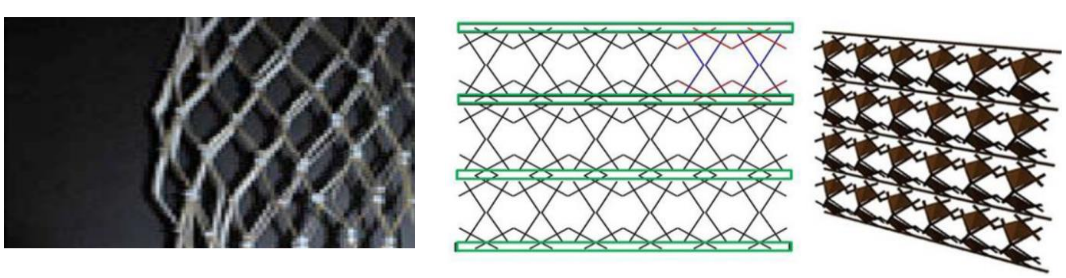


Figure 28: Pantographic decorative structure, (Asefi & Shoaee 2018).

It should be noted that designing kinetic facades for their aesthetic values should be integrated with building performance approaches. (Kronenburg, Lim & Chii 2003) discussed that designing for easier maintenance and using materials with life span that can be easily cleaned and repaired should be considered in order not to outdate the aesthetic life span of the building and would minimise the operation consumption of the building.

2.10.4 Evaluation strategies

Evaluating kinetic façade can be achieved in respect to environmental conditions. According to Sharaidin (2014), evaluating physical prototypes gives significant understanding of kinetic systems to ensure the effectiveness of kinetic facades in adapting to respond to local climate conditions. On the other hand, simulation techniques are more practical to understand kinetic systems performance in the early design phases and throughout the year especially for solar and daylight conditions where it is hard to be measured through physical prototypes.

Sharaidin & Salim (2012) highlighted that dynamic façade assessment and evaluation can be achieved through the following strategies:

1. Parametric and simulation tools that evaluate the behaviour and the performance of facades in relation to the environment and building characteristics.
2. The performance of the building that was predicted during the performance-based design process can be used as an evaluation tool.
3. Small-scale prototypes to be used to evaluate and understand the complexity of kinetic façade when it relates to kinetic façade behaviour, materials and movement mechanisms.
4. On site actual measurements to have the optimal prediction and the real performance of the proposed kinetic façade and to validate the measurements provided by simulation processes and small-scale prototypes.

2.10.5 Implementation strategies

The key elements for kinetic facade successful implementation strategies are the good understanding of adaptive systems, reliability, movement mechanism simulation and durability. Moreover, selecting adaptive systems, materials and fabrics require a good knowledge of kinetic design to make it successful. In addition, proper evaluation for designing kinetic facades provides a bigger picture of the design difficulties and obstacles that may happen during the operation of the building such as mechanical and electronic components that need proper assessment and prediction of their cost and technology, (Sharaidin & Salim 2012).

On the other hand, Loonen et al. (2016) highlighted that the proper implementation of designing kinetic façade can be applied through virtual rapid prototyping to assess materials, oriented systems, and to identify alternatives of the design development of the façade. In addition, exploration of control strategies and HVAC system sizing maximize the performance of the proposed design of kinetic facades in reference to virtual testing of occupant behaviour and environmental variable parameters.

2.11 Kinetic façade materials

Developing kinetic façade materials was working in parallel with developing kinetic façade in terms of typologies patterns and movement mechanism in the last decade, specifically when there were new products offered in the market that gave better opportunities for innovating new systems and new components.

Selecting kinetic façade materials is an important phase for developing kinetic systems. Perino & Serra (2015) highlighted that the objective of recognising kinetic materials is important to characterise the behaviour of kinetic façade and to build multi-functional adaptive modules. Therefore, this phase should be a preliminary step during the design process of kinetic systems.

Sharaidin (2014) agreed and identified that efficient kinetic systems can be implemented by using flexible materials, maintaining materials robustness, reduce the use of heavy materials and maintaining kinetic structures.

Marysse (2016) and López et al. (2015) categorized kinetic materials into two categories; active and smart materials. They stated that active materials would stretch, bend or fold while adjusting the material properties. On the other hand, smart materials would have the same facilities with the ability to cowhand their shapes, colour, transparency and stiffness. However, both categories are usually repeatable and reversible and able to exchange energy with no access to external power.

Table 2 illustrates some examples of active materials that can be used in kinetic facades with their possible functionalities:

Table 2: Kinetic façade active materials and identifying their function, (Marysse 2016)

Function	Components			
Heat storage	Phase change materials	Thermotropics	Light reactive materials	
(De)humidification	Humidity reactive materials	Silica gel		
Natural ventilation	Carbon dioxide reactive materials			
Daylight	Chromics (thermo/photo/electro)	Thermotropics	Vegetation	Liquid crystals/ Suspended particles
Overheating control	Chromics (thermo/electro)	Tropics (thermo/photo)	Vegetation	Phase change materials
Vision	Electrochromics	Thermotropics	Vegetation	Liquid crystals
Wind & water	Breathable fabrics		Vegetation	
Acoustics	Piezoelectrics			

In addition, Perino & Serra (2015) have listed the most used kinetic materials that are also related to the typologies of shading systems such as gas filled panels, PCM, high insulated materials, non-conventicle glazing, and coating with membrane and with special behaviour like photocatalytic coating. It should be noted that these materials, among others show the most capable applications.

In the application of kinetic facades and in reference to the previously discussed case studies, Jaen Novel in Arab institute has photo electric cells controlled to moderate light levels which are made of metal lattice, glass and aluminium. On the other hand, Al Bahar Tower in Abu Dhabi used PTFE cladding system that function as a kinetic Mashrabiya, whereas Yeosu Thematic Pavilion used fines made from fibre glass reinforced polymers for high tensile skin. On the other hand, Kiefer Showroom has used stainless steel for their folding shades.

Sharaidin (2014) concluded that indicating the link between materials physicality and the kinetic behaviour should be considered during the design process of kinetic movement to avoid any operational and maintenance issues that were experienced throughout the development of kinetic systems.

2.12 Summary of Chapter 2: Literature Review

Table 3: Literature review summary and findings

Literature section	Findings	Author	Year of publication
The impact of kinetic façade on building performance	Kinetic façade would achieve a reduction of 30% for heating and cooling compared to a building with no shading system	Alotaibi	2015
	The façade consumes 25% of the building total energy demand	Bacha & Bourbia	2016
	Shading would achieve 13.75% of energy savings in all climate zones	Elzeyadi	2017
	An office building in Denmark managed to get a reduction in energy consumption from 50 kwh/m2 to 25 kwh/m2	Johnsen & Winther	2015
	43% of energy savings can be achieved from kinetic shading whereas the reduction in indoor air temperature would range from 4.0 C° to 4.8 C°	Sharaidin & Salim	2012
	Cooling loads of a South facing office in Athens would be reduced by 9.8% compared to static façade	Sega Sufia Purnama & Sutanto	2018
	Hybrid double facades contribute in 23% energy savings	Wagdy et al.	2015
	Kinetic Aluminium window frame would result in 18-20% of energy savings compared to a building with no shading system	Ahmed et al.	2016
	Different configurations of kinetic louvers contribute in 28% to 30% energy reduction for heating and 28% to 33% for cooling	Hansanuwat	2010
	Kinetic strategies would achieve a reduction from 10-15% for HVAC systems with a reduction in operational cost for HVAC and artificial lighting from 10-40%	Marysse	2016
Factors affect shading system performance	There are several factors that affect the performance of shading systems; material, natural ventilation, sun control, daylighting, thermal insulation, moisture control, structural efficiency, mobile screens, technological solutions, automation systems and energy generation.	Romano et al.	2018
		Nady	2017

Kinetic shading typologies	Michael Fox classified kinetic structure to three typologies; deployable kinetic structure, embedded kinetic structure and dynamic kinetic structure	Fox & Kem	2009
	Mazier Asefi classified two types of kinetic structure; transformable tensile structure and transformable bending and compression structures and the motion of kinetic architecture into swivel, flap, pneumatic, rotate, slide, expand, fold ad gather	El-Zanfaly	2011
	William Zuk has classified kinetic architecture in eight classes and called them "Kinetiscism". Four of them are self-erecting structures, static structure, kinetic component and reversible architecture.	Zuk & Clark	1970
	Kinetic architecture applications were classified into three categories; kinetic structure systems, kinetic interiors and kinetic facades. kinetic façade behaviour was classified into four main categories; translation, rotation, scaling and motion	Nashaat et al.	2018
	Shading systems were classified based on the shape of the kinetic system to six typologies; automated blinds, egg crates, optical panels, thermal change planes, stretched fabrics and automated movable screens	Elzeyadi	2017
Kinetic Applications	CH2 building consist of automated movable screens with a tracking device of sun path and achieved a reduction of 85% on electricity consumption	Alotaibi	2015
	Kiefer Technic Showroom consists of Eggcrate shading typology that was user controlled to control the light admitted to the building.	Elzeyadi	2017
		Nady	2017
	Gherkin tower consist of optical shading that result in 85% solar protection through weather sensors and managed to achieve energy savings up to 50%	Elzeyadi	2017
		("30 St' Mary Axe (The Gherkin), London | Archinomy"	2019
		Raoa	2014

	Saint-Gobain headquarters consist of thermal change panels which were able to adjust the room temperature by 10 to 12 degrees.	Elzeyadi	2017
		Winstanley	2019
	Burton Bar central library consist of fabric/ weave shading system and managed to achieve one-third reduction in the building energy demand	Elzeyadi	2017
		Kostelni	2015
	Expo Yeosu thematic pavilion consist of automated screens that generate energy by converting the elastic energy stored in the panels into electrical power	JUNGJOHANN et al.	2012
		Barozzi et al.	2016
	Arabic institute consist of geometric screens through actuators and sensors that respond to the intensity of sunlight- designed for cultural and aesthetic values	Meagher	2015
		El-Zanfaly	2011
	Kolding campus consist of deep screens automated façade that achieves 50% reduction in energy savings and reach an annual energy consumption to 36 kwH/m2/year	("SDU Campus Kolding / Henning Larsen Architects"	2015
		Aelenei et al.	2018
Key factors to help in designing kinetic façade	A summary of adaptive systems key elements are identified as follows: the purpose, the responsive function, operation, a combination of materials and systems, response time, spatial scale, visibility and the degree of adaptability	Aelenei, Aelenei & Vieira	2016
	The study listed building orientation, position and materials, shading devises, windows type and location and roof shapes as the main parameters and design elements affect kinetic shading	Nady	2017
	The study mentioned that design decisions of kinetic façade are associated with kinetic mechanism and components to ensure the effectiveness of the façade operation	Sharaidin	2014
	The study highlighted the external factors that affect kinetic shading; solar radiation, visual and thermal comfort, outdoor temperature and humidity, wind and precipitation including natural ventilation and outdoor noise of the building.	Aelenei, Aelenei & Vieira	2016
		Johnsen & Winther	2015

	The highest external factors that affect the design of the buildings with 82% for solar radiation and 76% temperature		Aelenei, Aelenei & Vieira	2016
			Johnsen & Winther	2015
Design Stages	The early design decisions should take into consideration the design system, energy performance, movement mechanism, construction methodology, materials and the consultant experience		Sharaidin	2014
	Designing kinetic facades should start with design sketches and followed with digital simulation that validate and define the performance and the required measures of the proposed façade in real conditions. After that, a physical model prototype would be required for on-site experiments.		Sharaidin & Salim	2012
Design Strategies	Energy Performance-based design	The study adopted a working mechanism related to performance environmental simulation by using parametric design modelling in relation to daylight levels	Sharaidin & Salim	2012
		Designing buildings to have energy conscious façade should be constructed with strength and stability, control of heat, durable, control of air and vapour, fire resistance and cost effective	Nady	2017
		Multi design strategies were adopted by researchers to achieve the required building performance	Sharaidin	2014
	Daylighting control-based design	Arab institute in Paris is a notable example on daylight control where circular shutters operated as camera lenses in response to daylighting	Nady	2017
		Kinetic façade can be linked by daylight simulation tools where plugins can be connected to perform daylight analysis and can be connected to the rotation, size and opening of kinetic geometrics	Elghazi et al.	2014

		Adjusting kinetic materials is concerned with material's light transmittance properties where smart elements are able to adjust their optical properties to modulate daylight levels and solar energy	Elghazi et al.	2013
	Thermal control-based design	Sun radiation should be adapted through developed devices to result in efficient designs by protecting and filtering layers, sun breakers, louvers and any other kinetic shading	P. Jekot	2008
		The study consists of shadow simulation of static shading through simulation software, then a kinetic façade was developed based on the percentage of the shadowed area as a thermal design strategy.	Sega Sufia Purnama & Sutanto	2018
		Designing kinetic facades to achieve thermal comfort and the required daylighting levels can be integrated together whether it is controlled by the users or the computer or even based on a natural reaction	Bacha & Bourbia	2016
	Aesthetic control-based design	Origami patterns were explored through paper folding techniques based on shape, sequence and the relationship of geometric rules and folding morphology for kinetic façade development	Elghazi et al.	2014
		Adaptive decorative structures such as Pantographic which looks like scissors elements can be adopted as a kinetic system for their aesthetic values	Asefi & Shoaee	2018
		Designing for easier maintenance and using materials with life span should be considered in order not to outdate the aesthetic life span of the building	Kronenburg, Lim & Chii	2003
Evaluation Strategies	Evaluating physical prototypes gives significant understanding of kinetic systems to ensure the effectiveness of kinetic facades		Sharaidin	2014
	Dynamic façade evaluation can be achieved through Parametric and simulation tools, predicting performance-based design, Small-scale prototypes and on-site actual measurements.		Sharaidin & Salim	2012

Implementation Strategies	The key elements for kinetic facade successful implementation strategies are the good understanding of adaptive systems, reliability, movement mechanism simulation, durability and the proper evaluation for designing kinetic facades	Sharaidin & Salim	2012
	A proper implementation can be applied through virtual rapid prototyping to assess materials, oriented systems, identifying alternatives and exploring control strategies and HVAC systems	Loonen et al.	2016
Kinetic façade Materials	The objective of recognising kinetic materials is important to characterise the behaviour of kinetic façade and to build multi-functional adaptive modules	Perino & Serra	2015
	Efficient kinetic systems can be implemented by using flexible materials, maintaining materials robustness, reduce the use of heavy materials and maintaining kinetic structures	Sharaidin	2014
	kinetic materials into two categories; active and smart materials, , both categories are usually repeatable and reversible and able to exchange energy with no access to external power	Marysse	2016
		López et al.	2015
	Most used kinetic materials are gas filled panels, PCM, high insulated materials, non-conventicle glazing, coating with membrane and with special behaviour like photocatalytic coating	Perino & Serra	2015

This summery would assess the researcher in selecting the proper kinetic typology in reference to the targeted energy performance based on the key factors and the previous application of kinetic systems indicated in the literature. Furthermore, it would be used as reference throughout the selected design strategies and the design development of the proposed kinetic system in this research. In addition, validating the results generated from both site experiment and simulation of the selected case study in conjunction with data analysis and discussion of the research results.

CHAPTER THREE

METHODOLOGY

Chapter 3 Methodology

In this chapter, the methodologies used to implement kinetic façade strategies will be highlighted in reference to the proposed kinetic systems that was identified in the literature. Many methodologies were identified to investigate the performance of kinetic systems. Each one of them has negative and positive features that will be explained in detail in this chapter.

Nowadays, modern methods with different technologies were applied to test kinetic systems to get better and accurate results instead of manual tools that were used to assess shading performance through mathematical calculations. Therefore, the methodologies that will be discussed in this section consist of field experimental measurements, parametric tools, simulation tools and laboratories scaled prototypes. On the other hand, most of the research in this area of study was conducted using simulation tools or/and experimental techniques to get real life results along with high quality of accurate building performance results.

3.1 Parametric tools

Parametric tools have been used recently to assess the performance of kinetic systems. Elghazi et al. (2014) Identified that the potential of parametric modelling helps to generate various distinct forms by modelling different designs that can be connected through mathematical operations and multi variables and parameters to result in a parametric space with series of design alternatives. The advantage of parametric tools is that it allows the users to have the possibility to adjust any parameter without the need of repeating the process and generating different models. Moreover, the exploration of new designs with respect to various parameters helps architect and designers to propose optimal designs and behaviours that respond to different climates and environmental conditions.

Bacha & Bourbia (2016) agreed and mentioned that parametric tools can be used as a design tool as it allow the designers to get accurate results of complex simulation models and use it at early design stages where it is possible to get an optimal envelope with multiple design values for specific environments and conditions. Parametric architecture has introduced new design approaches and technologies that involve quantifying and sketching new configurations and behaviours in nature to advanced programs to assess designers in investigating new patterns and geometries in relation to performative capabilities and propensities of kinetic systems.

In addition, parametric tools provide model variation of the selected parameters in reference to the simulation conducted for daylight performance. Hofer et al. (2016) explained how parametric tools are able to study the appearance of the building envelope and solar radiation of PV dynamic modules by investigating the module shading and solar irradiance, which can be coupled with electrical model to analyse the electrical performance. In this study, current voltage curves of PV modules were calculated to evaluate the electrical energy consumption for different parameters and module interconnections.

Mahmoud & Elghazi (2016) have used Rhino and DIVA to generate a parametric analysis of hexagonal pattern. The study standard dimension of WWR was set as 20% to be used as a base case and the type of motion was represented through a daylight simulation to achieve the optimal daylight adequacy. The integration between Rhino-DIVA and Grasshopper created a parametric interface for daylight evaluation to reach an optimal solution.

3.1.1 Grasshopper

Grasshopper is one of the parametric design tools that were developed by David Rutten, Robert McNeel & associates in 2007 as a Rhinoceros software plugin, (Elghazi et al. 2014). It is considered as a graphical algorithm editor that allow the user to write custom scripts by VB.NET or C# through different components to help designers generate parametric configurations quickly with no formal scripting.

Hofer et al. (2016) designed a parametric 3D shading system using Rhinoceros 3D software through Grasshopper plugin to generate a rectangular pattern. The resulting design is a combination of PV modules represented in multiple rectangular surfaces that would be rotated in different range of angles in reference to solar azimuth or attitude direction or both. Grasshopper allows the model to have an adjustable distance for rotation behind the module plane in order to allow the mechanical system to get a proper simulation.

Bacha & Bourbia (2016) used Grasshopper plugin to facilitate the exchange between simulation software to enable importing the solar path with real time data to be connected with the proposed shading system. This allows the system to response to the direct effect of solar position and angle to generate a more complex system with adjustable kinetic shading components. On the other hand, Wagdy et al. (2015) chose Rhino and Grasshopper to generate a folding model for Kaleidocycle kinetic façade to determine the configuration of the optimal value to achieve the lowest energy consumption.

Sharaidin, Burry & Salim (2012) used Grasshopper with the integration of Ecotect software to select the percentage of optimal closing and opening of a kinetic pattern in reference to daylight simulation. This allows the designers to get the optimal outcome of the best conceivable geometric configurations.

3.2 Computer simulation method

Computer simulation tools have been accepted recently due to its accuracy and availability. It was developed with high computing power to enable the user to predict real life measurements. Moreover, simulation tools allow the user to adjust the model parameters to get the required data in a short period for the whole year. The time required for this method depends on the size of the space, level of accuracy, details and what parameters are selected for the area of study, (El Geresi & Abu Hijleh 2011) & (Ahmed, Abdel-Rahman & Bady 2016).

Loonen et al. (2016) conducted a study of the current BPS software of adaptive systems and highlighted that the most powerful simulation tools for predicting energy performance and comfort of buildings that have used in most studies and was validated for its capabilities are; EnergyPlus, IES VE, ESP-r, TRNSYS and ICE. In this section, some examples of studies conducted using some of these simulation software will be discussed.

El Geresi & Abu Hijleh (2011) applied computer tools to test external louvers for energy saving and glare effect to get the advantage of simulation tools in saving time and money with the possibility of adjusting material's properties and system's parameters. The study was conducted in UAE and used IES-VE software as a computer tool due to its capabilities in achieving quick feedback and the flexibility in manipulating models and inserting real building data.

Furthermore, Elzeyadi (2017) conducted a simulation on six typologies of kinetic shading using IES-VE software using its parametric simulation engine to test the performance of these shading typologies on a South façade with single sided typical floor. The simulation used thermal loads engines, Apache, and Radiance to assess glare, daylighting and both solar heat gain coefficient (CHGC) and solar insolation.

In addition, Ahmed, Abdel-Rahman & Bady (2016) assessed different configuration of dynamic louvers in an office building in Abu Dhabi, UAE, where HVAC and lighting were the main aspect of comparison and outcome for this study. IES-VE simulation software was selected for this study due to its accuracy and simplicity. Specifically, when it is used to control artificial lighting and HVAC systems based on the overall energy consumption.

Sega Sufia Purnama & Sutanto (2018) have applied simulation tools at the first stage of his study to discuss the impact of dynamic louvers in a high rise building in Jakarta. SketchUp 2017 software was used to implement the simulation by measuring the shadow percentage of each type of shading. The configuration that had higher shadow effect was selected for a better performance to obtain further calculations.

Elghazi et al. (2014) have used an integration of digital simulation tools and Grasshopper by using a plugin called Geco to investigate and analyse the digital model through Autodesk's Ecotect program. On the other hand, Rhinoceros 3D tools such as DIVA would be able to connect Grasshopper components with the architectural model to perform daylight analysis via Radiance and DAYSIM. Bacha & Bourbia (2016) used the same approach to explore multi configurations of shading designs for daylight utilization, radiation protection and energy consumption.

Loonen et al. (2016) discussed the challenges of simulation tools to investigate the performance of adaptive façade by indicating the pros and cons of modelling and simulation tools. They stated that simulation tools provide a mutual impact of design and performance aspects where a strong contribution in construction market can be achieved in innovative technologies. However, the complexity of predicting the performance of adaptive systems in a tool used to assess a static element is a challenge for researchers and requires developing a simulation strategy according to their resources and requirements.

Bacha & Bourbia (2016) concluded that simulation tools are not able accurately to consider kinetic systems but rather optimize the connection between static parameters. Therefore, parametric tools were developed to redefine architecture to enable architects and designers to innovate and construct new buildings with both qualitative and quantitative circumstances.

3.3 Field experimental measurements

Experimental techniques enable the researcher to get real life measurements that can be analysed in reference to both operational and climatic data, (Ahmed, Abdel-Rahman & Bady 2016). Sharaidin (2014) added that conducting on site measurements and exploring the design of kinetic systems offer an alternative technique to evaluate the proposed design in response to environmental conditions, which reinforce the results collected from simulation tools to get a better understanding of the kinetic system and the challenges of dealing with physical experiment of the kinetic façade performance.

Ahmed et al. (2016) conducted an experimental work for a South oriented window that has a dynamic window frame can be adjusted vertically and rotate accordingly in an up and down motion located in Egypt. The window frame has a DC actuator and a motor which are connected to a temperature sensor that respond to a controlled computer with Grasshopper and Rhino. Moreover, air velocity meter was attached to the system to measure indoor air velocity and temperature along with indoor RH. The aim of this experiment is to identify the impact of energy consumption of kinetic system and to identify its advantages.

3.3.1 Laboratory scaled prototypes

Making prototypes helps the designers and researchers to assess the drive technologies and movement mechanism of kinetic systems. Moreover, physical prototype provides a better assessment of the main drive both replacement and maintenance of the spare part of the shading system to get the optimal rotating motion, (Sega Sufia Purnama & Sutanto 2018) & (Sharaidin 2014).

Sega Sufia Purnama & Sutanto (2018) have investigated the impact of shading system that was assessed through simulation tools in previous stages by making a prototype made from aluminium metal. The study investigated two parameters in making the prototype; drive technologies whether it is pneumatic, hydraulic and motor drive and shading system material. The performance of a shading system prototype was tested to investigate both indoor and outdoor temperature using an instrument called HOBO tool. This tool was placed inside a test box with specific measurement to get a better indication of the temperature enhancement of the shading system.

In addition, Elzeyadi (2017) have explored the impact of six shading typologies through six prototypes that was installed on the same façade using simplified materials during fall 2014 and 2015. The data was collected using an online data logger from the FIT facility for lux levels (lighting), RH, irradiance, temperature and solar insolation for the entire year. After that, the records of the data collected were inserted in CR310 Campbell Scientific data logger system for every second and minute.

It should be noted that a prototype of Al Bahar tower that was constructed in Abu Dhabi/ UAE which was identified in the Literature as one of the applications of kinetic façade has been implemented before the construction of the whole façade to ensure a proper coordination between the Mashrabiya, the steel frame and the concrete core for a better investigation of wind and fabric testing. Moreover, a laboratory test took place in Switzerland to test shading devices and mechanics, (Attia 2016).

3.4 A summary of research approaches

Table 4 illustrates a list of collected journals that adopted the methodologies listed in this section with similar research objectives, scope and title, which will be taken into consideration for selecting the best method and approach for the case study of this research.

Table 4: Methodology summery for investigating kinetic façade performance

Publication	Journal title	Year of publication	Authors	Purpose	Methods
The British University in Dubai (BUiD)	The energy saving potential of using the optimum external fixed louvers configurations in an Office Building in UAE climate condition	2011	Sherif Yahia El Geresi Bassam Abu Hijleh	Test shading system for energy savings and glare effect	Simulation model- IES-VE
Energy and Buildings 42 (2010) 1888–1895	The energy savings potential of using dynamic external louvers in an office building	2010	Fawwaz Hammada, Bassam Abu-Hijleh	To explore multiple configurations to evaluate the efficiency of dynamic louvers in a typical office building	Simulation model- IES-VE
Architectural Science Review	The impact of dynamic façade shading typologies on building energy performance and occupant's multi-comfort	2017	Ihab Elzeyadi	To compare the performance of different shading typologies in terms of energy savings, daylighting, glare and solar insolation management in an office space	Simulation model – IES-VE/ Full scale constructed prototypes
Fifth German-Austrian IBPSA Conference- RWTH Aachen University	DAYLIGHTING DRIVEN DESIGN: OPTIMIZING KALEIDOCYCLE	2014	Y. Elghazi1, A. Wagdy2, S. Mohamed3 and A. Hassan4	To enhance the daylighting of living room by employ a non-simplified shading	Simulation tools/ Parametric tools- Grasshopper

	FACADE FOR HOT ARID CLIMATE			technique formed by Kaleidocycle pattern	
Energy Science and Engineering 2016; 134–152	Parametric analysis and systems design of dynamic photovoltaic shading modules	2016	Johannes Hofer1, Abel Groenewolt2, Prageeth Jayathissa1, Zoltan Nagy1 & Arno Schlueter	To analyse solar insolation for complex dynamic shading situations and to find the best electrical layout for a given shading system and control strategy	Parametric tool-Grasshopper
Solar Energy 126 (2016) 111–127	Parametric-based designs for kinetic facades to optimize daylight performance: Comparing rotation and translation kinetic motion for hexagonal facade patterns	2016	Ayman Hassaan Ahmed Mahmoud Yomna Elghazi	To study the impact of kinetic motion of hexagonal pattern on South-facing skin to control the daylight distribution in an office space	Parametric tools Rhino/DIVA/Grasshopper
11th Conference on Advanced Building Skins, Oct 2016, Bern, Switzerland	Effect of kinetic facades on energy efficiency in office buildings -hot dry climates	2016	Cherif Ben Bacha, Fatiha Bourbia	To examine the effect of smart façades in the context of indoor thermal comfort and energy efficiency	Simulation tools/ Parametric tools-Grasshopper
IOP Conference Series: Earth and Environmental Science	Dynamic facade module prototype development for solar radiation prevention in high rise building	2018	Muhammad Sega Sufia Purnama and Dalhar Sutanto	To discuss the dynamic facade module prototype development in high rise building in Jakarta	Simulation/ Module prototype/ field measurements
Journal of Building Performance	Review of current status, requirements and opportunities for	2016	Roel C.G.M. Loonena , Fabio Favoinob∗ ,	To bring together and analyse the existing information of building	Simulation tools

Simulation, 2017	building performance simulation of adaptive facades		Jan L.M. Hensena and Mauro Overendb	performance simulation tools of adaptive façade	
Czech Technical University in Prague, Faculty of Architecture	Integration of Digital Simulation Tools with Parametric Designs to Evaluate Kinetic Façades for Daylight Performance	2012	Kamil Sharaidin1, Jane Burry2, Flora Salim3	To address limitations associated with incorporating performance criteria in the design of kinetic façades by integrating different simulation tools	Ecotect software/ Grasshopper
International Journal of Smart Grid and Clean Energy	Optimum energy consumption by using kinetic shading system for residential buildings in hot arid areas	2015	Mostafa M. S. Ahmed, Ali K. Abdel-Rahman, Mahmoud Bady, Essam K. Mahrous, M. Suzuki	To measure the influence of the new adaptive kinetic shading system in energy consumption within residential building	Field measurements
AEI 2015 Conference **March 24-27, 2015**	The Balance between Daylighting and Thermal Performance Based on Exploiting the Kaleidocycle Typology in Hot Arid Climate of Aswan, Egypt	2015	A. Wagdy, Y. Elghazi S, Abd alwahab, and A. Hassan	To identify the most efficient daylight and thermal performance by incorporating parametric optimization	Parametric tools / Grasshopper and Diva-for-Rhino

3.5 Research method and justification

Previous studies have used different research methodologies to evaluate and assess adaptive building façade. The focus in this research is to investigate the energy performance of kinetic façade on an existing building with fixed shading object. This will be done through the implementation of kinetic design strategies in response to three parameters; WWR of the building four elevations, the solar radiation in response to sun angle and exposure and the third parameter will be the functionality of the building that consider the purpose of the building and users comfort. The case study will act as a reference for investigating actual performance of kinetic shading and its results would be applicable within future design technologies.

The methodology of this research will be divided to four methods in a mixed methodology; the first stage will be incorporating the literature review through understanding the key factors affecting kinetic shading performance, kinetic shading typologies, the application of kinetic systems and the design development of kinetic systems. The second stage will be the observational approach of field measurements to identify the energy consumption of the building, temperature, RH and daylighting through lux levels indicators using an environmental meter provided by EXTECH instruments.

The third stage will be conducted using parametric tools to assess the researcher in getting the percentage of both closing and opening ratios of the proposed pattern configuration of the kinetic system through Grasshopper in reference WWR parameter that was selected in reference to targeted performance level of the building cooling loads. The fourth stage will be implemented using simulation tools to validate on site measurements and assess the performance of the proposed kinetic shading strategies of the proposed design that was proposed in reference to the cumulative process of the three parameters selected for this research.

Simulation process and modelling of the existing building with its internal heat gains will enable the researcher to validate the data collected through the site experiment. Moreover, to get an indication of the targeted performance level of the WWR to enable the researcher to propose kinetic system strategy which would be able to contribute in assessing the building envelope performance by bringing the mutual influence of design and performance aspects in a mutual influence to develop innovative strategies.

IES VE was selected as a simulation tool due to its capabilities and flexibilities in providing a quick feedback and manipulating models and inserting real building data especially that kinetic systems would consist of multi scenarios to be able to predict the overall annual performance of the building. Moreover, as the study is done in corporation with Dubai municipality to assess how adaptive systems can increase the rating of buildings through Saafat rating system, IES VE software was targeted to be used as a certified software for assessing building performance by conducting onsite measurements for an existing building and investigating the tolerance that we might get from simulation tools to validate the data collected.

The research stages of implementing simulation tools via IES VE and parametric tools via Grasshopper will be summarized as follows:

- The existing base case will be assessed via IES VE to validate on site measurement depending on the internal gains in reference to the site visit date.
- The targeted performance level will be calculated and analysed based on the data conducted from IES VE in three seasons; 21st of March, 21st of June and 21st of December in three different timings; 8:30 AM, 12:30 PM and 5:30 PM. The process of calculating the targeted performance level is conducted by adjusting the WWR in each façade by manipulating the void area in reference to the reduction of cooling loads expected from the previous studies indicated in the LR.
- The selected WWR will be inserted as a parameter for adjusting opening and closing ratios in each pattern through Grasshopper.
- Base case sun cast measurements will be applied using IES VE to determine the solar exposure of each façade.
- Final scenarios (9 scenarios) will be generated post the cumulative process of the kinetic design strategy to be simulated through IES VE to determine the enhancement of building performance in relation to adopting kinetic systems.
- An estimation of cooling loads and energy reduction will be the outcome of this study.

- Parametric design tools will be explored to formulate kinetic facades that interact in reference to the proposed parameter of WWR.
- Kinetic design strategies will be explored during this study to be used at early design stage in future research methodologies.

Analysing the data conducted from the methodologies listed above will be based on the previously mentioned studies related to assessing kinetic systems and their analytical methods of studying similar area of research.

3.6 Methodological framework

The following figure describes the methodological framework of this research starting from data collection to future design recommendation, which is developed to propose an optimal kinetic system for the selected case study.

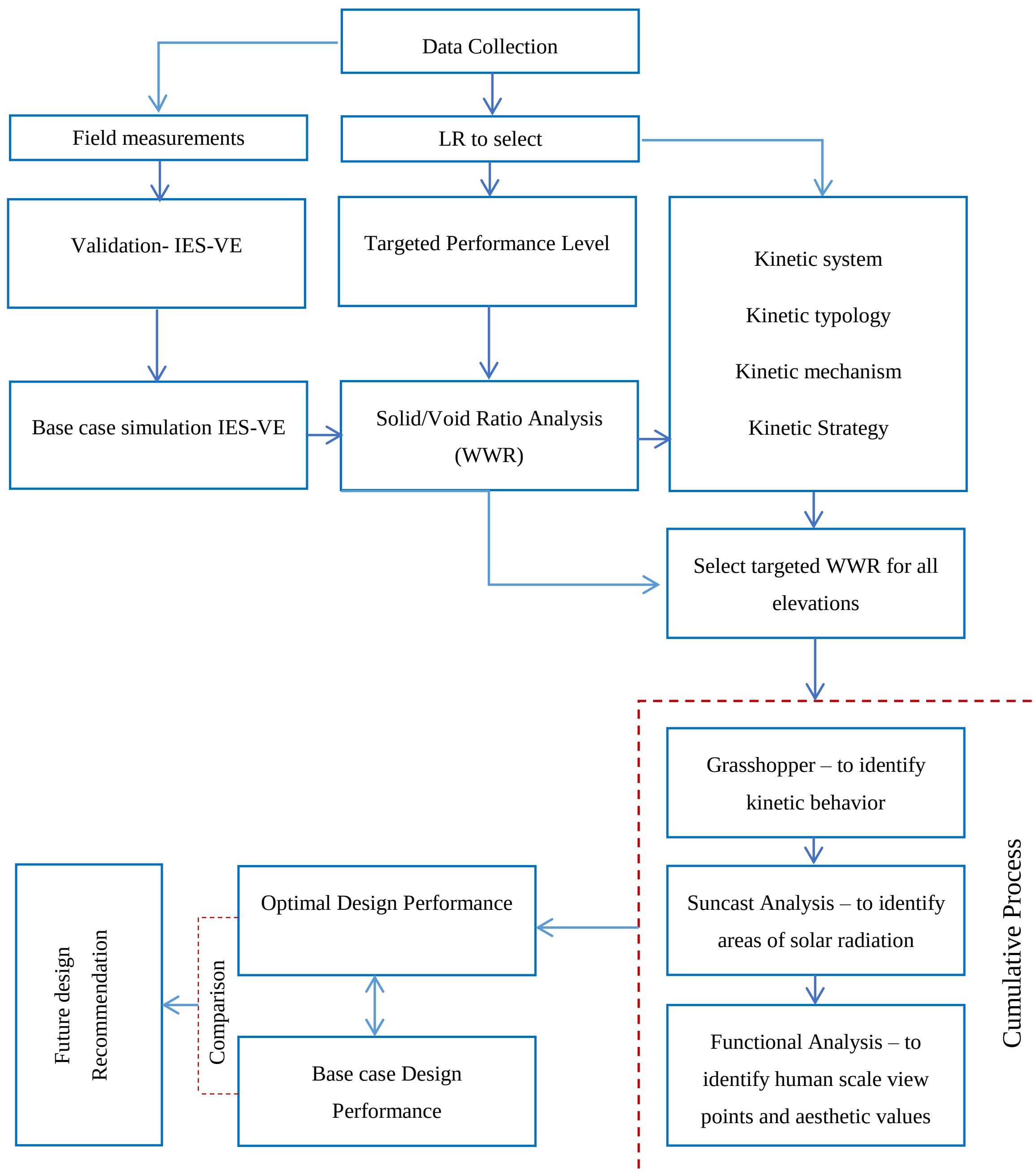


Figure 29: Research approach methodological framework

3.7 Summary of chapter 3: Methodology

Designing kinetic façade is a complex task starting from adopting a kinetic system, selecting a design strategy and methodological approach for evaluating the system. Therefore, papers and journals where selected to discuss the dynamic variables in each method and look for similarities in different approaches to result in an efficient and proper methodology for this area of study.

The focus of this research is to investigate the pros and cons of each methodology on the related topic in relation to achieving thermal comfort, daylighting levels and the targeted energy reduction of kinetic systems. Research have used multi methodologies such simulation and parametric tools with experimental tools to get real measurements.

Parametric tools have been developed recently and used in most of the recent studies due to its abilities to evaluate kinetic parameters and behaviours of kinetic systems such as using Rhino with DIVA and Grasshopper. The selected parameters can be inserted manually and programmed using the software or it can be connected to plugins that response to daylighting simulation and environmental analysis. However, simulation tools are still being used due to its simplicity in conducting the analysis of buildings performance, accuracy and availability to researches.

IES VE have been explored by some studies and validated for its capabilities of predicting the energy performance of kinetic systems and comfort of buildings. Moreover, it was considered as a friendly tool that saves time and money through its flexibility in manipulating models and inserting real building data with the possibility of adjusting material's properties and system's parameters to achieve optimal results.

Field measurements were implemented in the studies that had a longer period for conducting the research and financial support as we have seen in similar topics where people have made kinetic systems from simple materials and kept then for a full year for a proper assessment. Furthermore, some researches have tested kinetic systems by making laboratory small scale and large-scale porotypes to validate the results given by simulation tools.

The methodology of this research will be a mixed methodology; incorporating literature review data, observational approach of field measurements to validate the use of IES VE as a simulation tool, parametric tools through Grasshopper in reference WWR parameter and using simulation tools to validate on site measurements and assess the performance of the proposed kinetic systems in reference to solar radiation and the functionality of the building to result in occupants comfort.

CHAPTER FOUR

THE CASE OF DUBAI FRAME

Chapter 4 The case of Dubai Frame

4.1 Introduction

The first part of this chapter overviews the selected case study by descripting the concept design of the building along with presenting a detailed site analysis that covers its location, orientation, natural features, etc., followed by, a climatic analysis of Dubai to include temperature, rainfall, humidity and wind data that will be used during the simulation process. Furthermore, the building construction materials are illustrated in reference to the existing conditions as described in the building's specification and construction drawings.

The second part identifies the validation process that is used to validate the selection of IES VE software for simulation. The validation conducted by comparing both, the building energy bills with results of the base case simulation, and comparing daylighting levels measured through a site experiment with the ones obtained from the simulation. In this process, internal heat gains and default electricity lighting figures were used as an input in IES setting. On the other hand, the third part presents the data conducted of the base case daylighting levels and total electricity and cooling loads for nine scenarios that are described in SIM 1 to SIM 9 to be used in the next chapter for comparing the results of the base case and the proposed kinetic system.

The fourth part of this chapter discusses design development of the proposed kinetic system in details through five stages; selecting kinetic system, selecting kinetic typology, selecting kinetic mechanisms, selecting kinetic strategy and selecting kinetic scenarios, which are conducted through a cumulative process that combines all factors related to the proposed kinetic system strategies in order to generate an optimal design of the proposed kinetic behaviour.

The proposed kinetic strategies include (i) Energy performance-based design strategy that is achieved through WWR analysis and a parametric model using Grasshopper plugin to identify the kinetic scenarios generated in respect to the targeted energy reduction levels. (ii) Thermal performance based-design strategy where sun cast images are analysed to identify the impact of sun exposure on the proposed kinetic scenarios. (iii) Aesthetic performance based-design strategy that identifies aesthetic values and areas at the building that would be affected from the kinetic system.

4.2 Case study selection

Dubai Frame is selected as a case study for assessing the impact of kinetic systems when it is applied on an existing high-rise building. Dubai Frame is the latest cultural landmark in UAE as it was opened to public on the 1st of January 2018. It is also considered an iconic building due to its spectacular location where it is positioned to overlook the new Dubai from one side to South and the old city from the other side facing North.

The building consists of a museum, two towers that contain elevators shafts, stairs and service rooms. The upper bridge links the two towers in a sky view deck where visitors of the building can celebrate the story of Dubai starting from its early establishment to its future development, (Dubai Frame building opens to public 2018). Figure 30 shows a selection of Dubai Frame images that describe its main design elements, the cost of the building, size, pattern and visitors journey that they would experience through the building, (Dubai Frame building opens to public 2018).

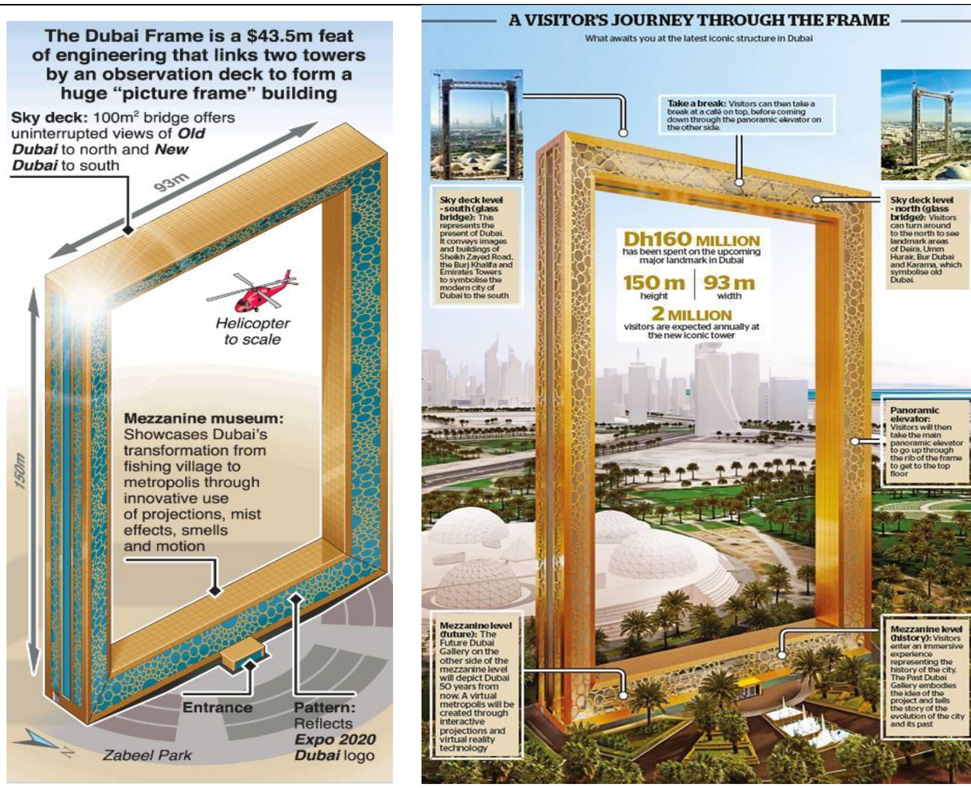


Figure 30: Dubai Frame design and visitors' journey, (Dubai Frame building opens to public 2018)

Dubai Frame known as the biggest picture frame on the planet; it is 150 M tall and 93 M wide. The concept design of the building was selected based on a design competition held by the Government of Dubai. The winner of the competition was Fernando Donis and the building was developed and operated by Dubai Municipality. Figure 31 shows real pictures of Dubai Frame from construction until completion.

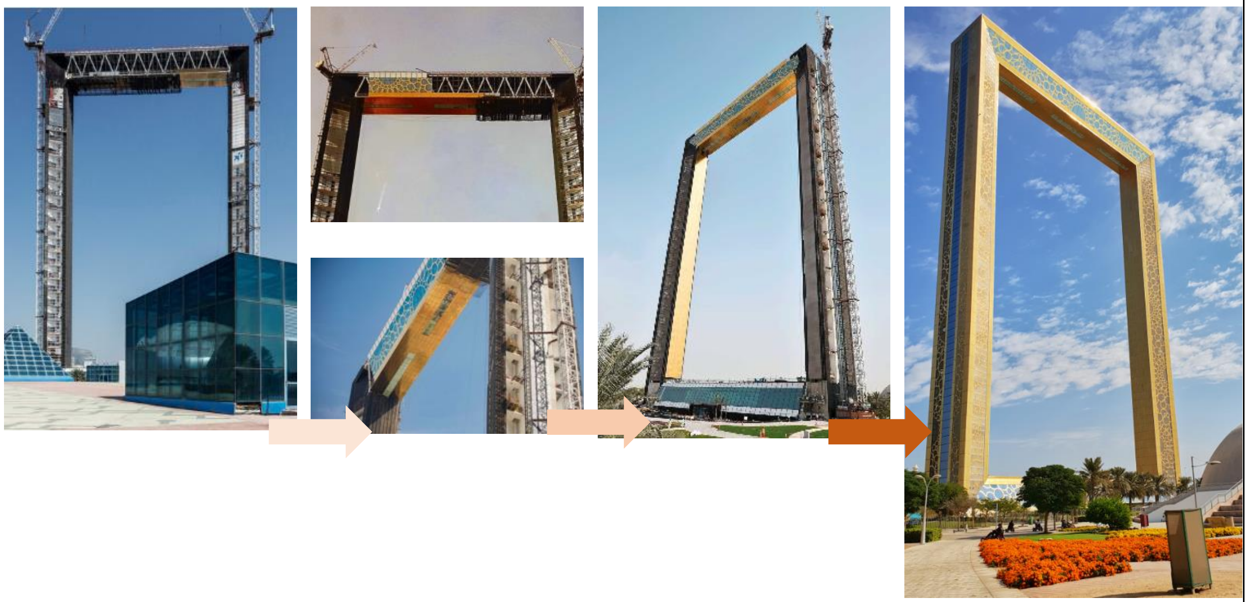


Figure 31: Dubai Frame from construction until completion

The building is made of glass, aluminium, steel and reinforced concrete. The design of the exterior façade was inspired from Expo 2020 Dubai logo. The story behind Expo 2020 logo is a ring found in an archaeological area where civilisation was inhabited in the desert of Dubai 4,000 years ago. A meaningful message behind this logo is telling the world the Emirates civilization has deep roots as stated by his highness Sheikh Mohammed Bin Rashid. Figure 32 shows the image of the ring and Expo 2020 logo that was used as an inspiration of Dubai Frame external façade pattern, ("Expo 2020 Dubai" 2019).

In addition, Dubai Frame was designed to react to the wind loads such as porous cladding and a damper in the building to reduce the impact of wind loads while maintaining the aesthetic value of the structure, (Operation Team 2019).

Figure 32: The story behind Expo 2020 logo and Dubai frame external façade, ("About Us | Dubai Frame" 2019) ("Expo 2020 Dubai" 2019)

4.2.1 Site analysis

Dubai Frame is located in Zabeel Park, Karama, Dubai. Zabeel Park is bounded by one of the main roads in Dubai (Sheikh Zayed Road) that connect the city to Sharjah Emirate from the North and Abu Dhabi Emirate from the South. Moreover, Zabeel Park is one of the main parks that is close to the heart of Dubai as it is 6.5 KM away from Burj Khalifa and Dubai Downtown. Figure 33 shows the location of Zabeel Park in reference to Dubai main landmarks and districts.

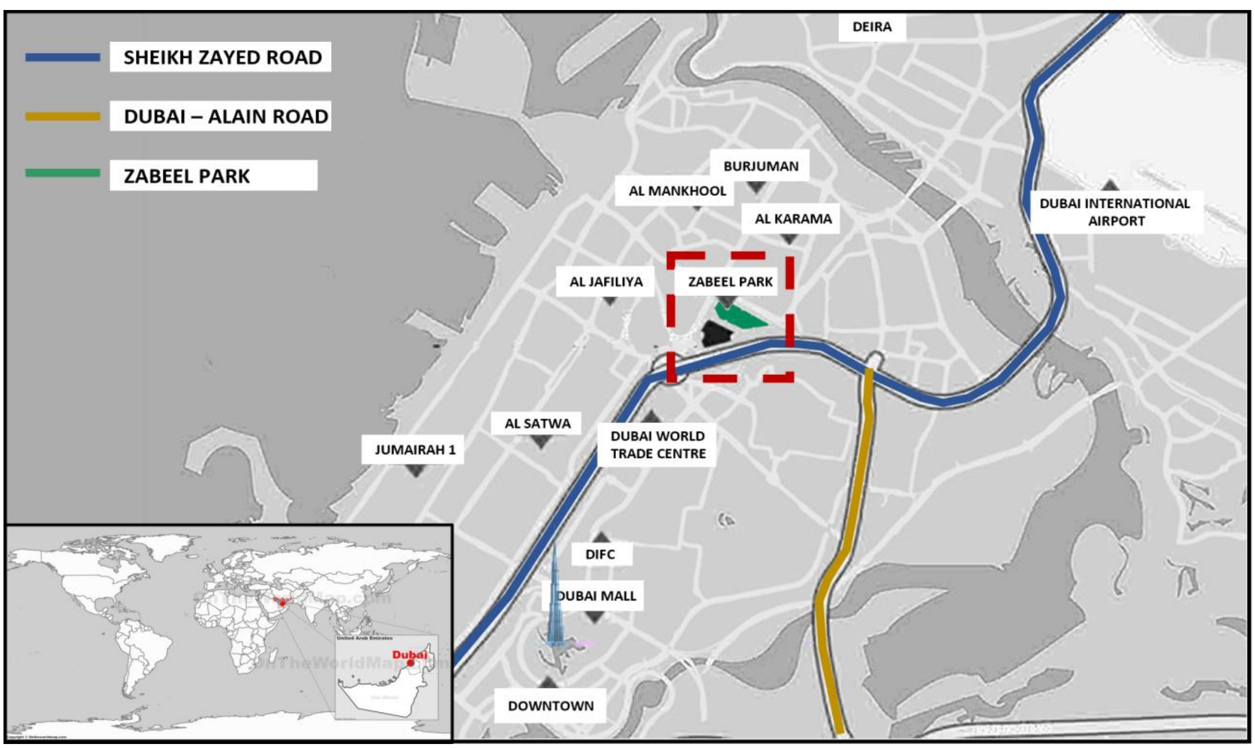


Figure 33: Zabeel Park location map

Dubai Frame is located in the East side of Zabeel Park, which is accessible through Gate 04 where tickets are provided for the visitors who are wishing to enjoy the view of the building. On the other hand, the landscaping and the natural features, that surround the building, allow the visitors to have a better experience while having a direct view of the landscape beneath. It also enables the visitors to stroll around before and after visiting the building. Figure 34 shows the location of Dubai Frame in respect to Zabeel Park with an indication of its natural features, entrances, parking and the direction of its views.

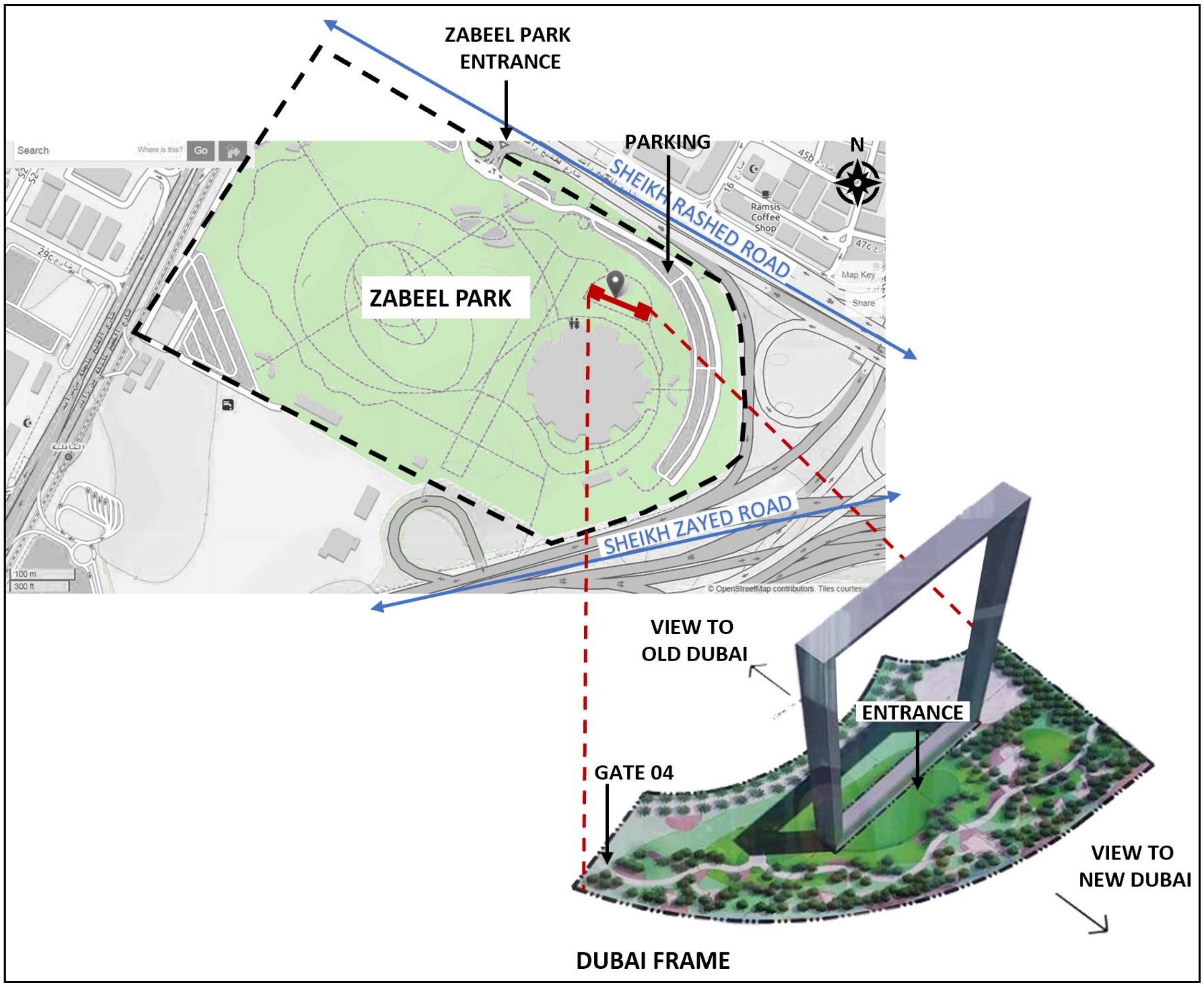


Figure 34: Dubai Frame location map

4.2.2 Climatic Analysis

UAE has a hot humid climate with hot summers, little rain falls and warm winters. However, recently more rain was experienced but still with little amounts due the current climate change that is affecting the global climate, ("Climate and average weather in United Arab Emirates" 2019). In this section, climatic figures of temperature, rainfall, humidity and wind in Dubai will be presented to be used as climatic data during the simulation process.

4.2.2.1 Temperature in Dubai

The temperature in Dubai would reach up to 47°C and ranges between 35 - 40°C, (Ministry of Environment and Water 2015). However, "Climate and average weather in United Arab Emirates" (2019) mentioned that Dubai average temperature in 2019 would be 25°C in winter and at night, it would drop to 15°C. On the other hand, the warmest month is August and coldest is January. Figure 35 shows the average minimum and maximum temperature in Dubai over the year. Figure 36 shows the average monthly sun hours in Dubai over the year.

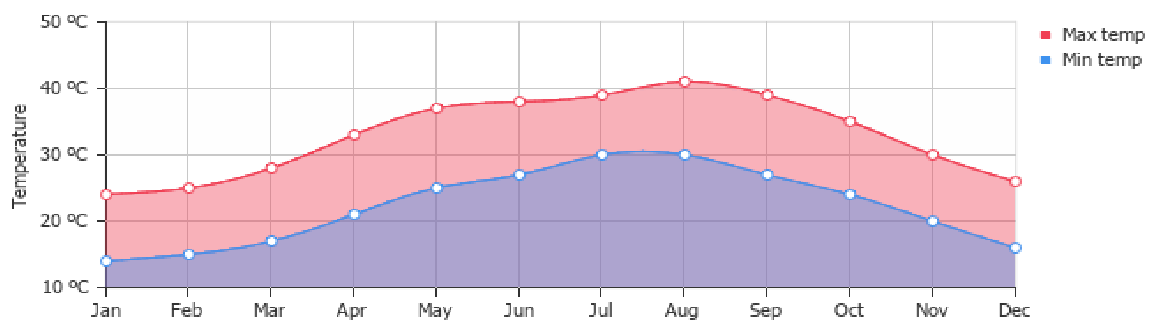


Figure 35: Average minimum and maximum temperature in Dubai over the year, ("Climate and average weather in United Arab Emirates" 2019)

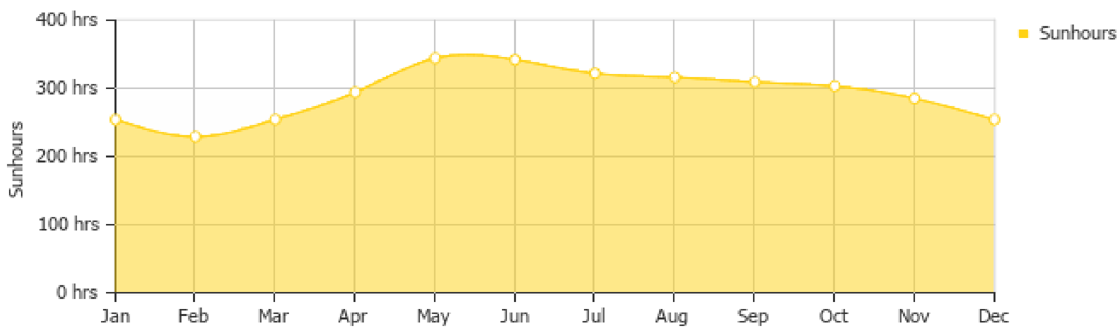


Figure 36: Average monthly sun hours in Dubai, ("Climate and average weather in United Arab Emirates" 2019)

4.2.2.2 Rainfall in Dubai

UAE has low rainfall. However, Ministry of Environment and Water (2015) stated that December and January are usually accompanied by thunderstorms. On the other hand, February is considered the wettest month and August is considered the driest month. ("Climate and average weather in United Arab Emirates" 2019). Figure 37 shows the average precipitation in Dubai over the year.

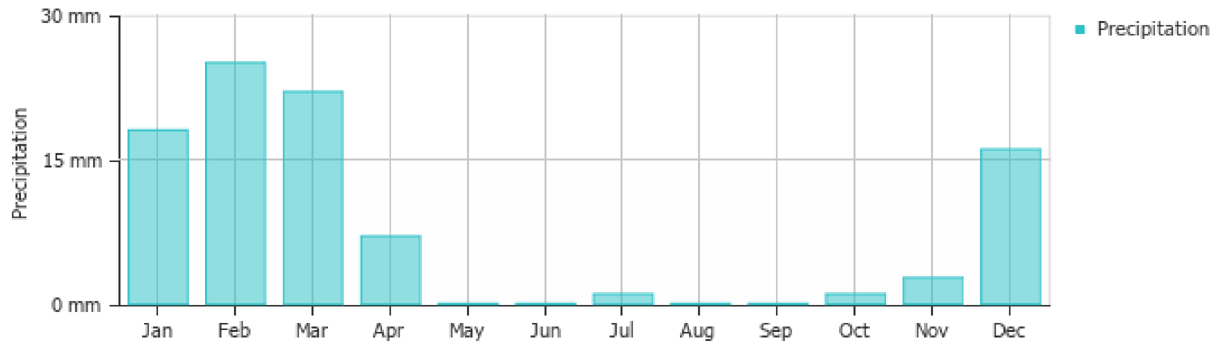


Figure 37: Average precipitation in Dubai over the year, ("Climate and average weather in United Arab Emirates" 2019)

4.2.2.3 Humidity in Dubai

The average relative humidity in Dubai ranges between 50% and 65%, ("Climate and average weather in United Arab Emirates" 2019). However, in summer, the humidity ranges from 60% to 100% in UAE, as it gets higher in coastal areas and lower in inland areas, (Ministry of Environment and Water 2015). Figure 38 shows the average relative humidity in Dubai over the year.

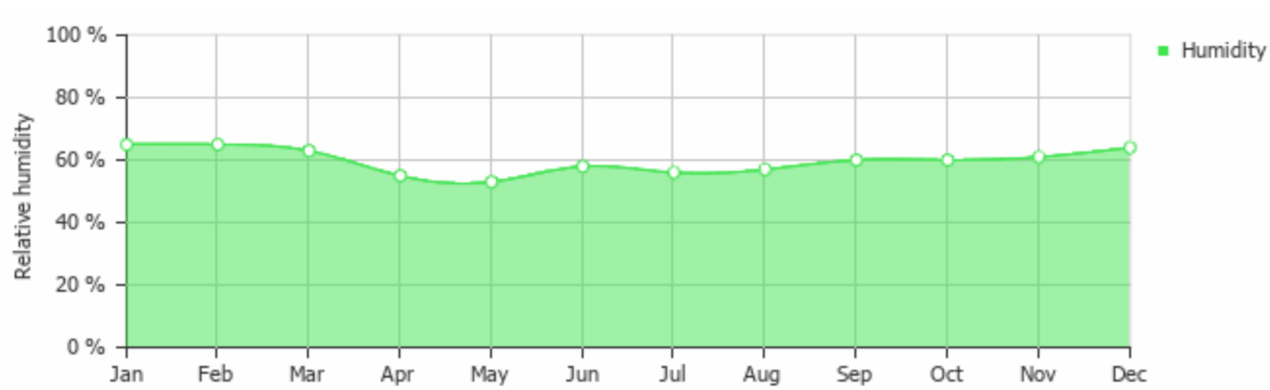


Figure 38: Average relative humidity in Dubai over the year, ("Climate and average weather in United Arab Emirates" 2019)

4.2.2.4 Wind in Dubai

Dubai has an average wind speed that ranges from 10 kmph to 20 kmph, ("Dubai Historical Weather" 2019). However, stronger wind blows across UAE in spring and latest summer months and consists of two types; Northern dry wind and Eastern humid wind, (Ministry of Environment and Water 2015). Figure 39 shows the average and maximum wind speed in March 2018 in Dubai. Figure 40 shows the average and maximum wind speed in June 2018 in Dubai and Figure 41 shows average and maximum wind speed in December 2018 in Dubai.

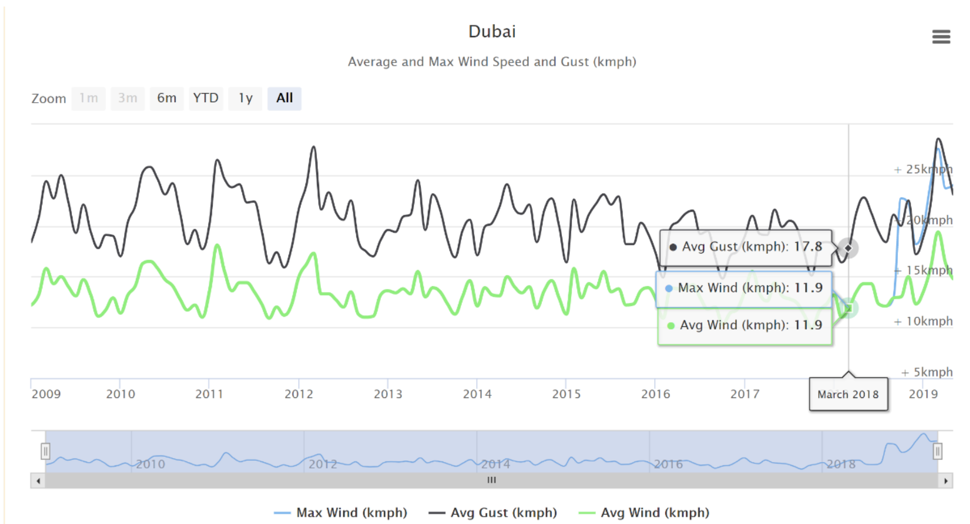


Figure 39: Average and maximum wind speed in March 2018 in Dubai, ("Dubai Historical Weather" 2019)

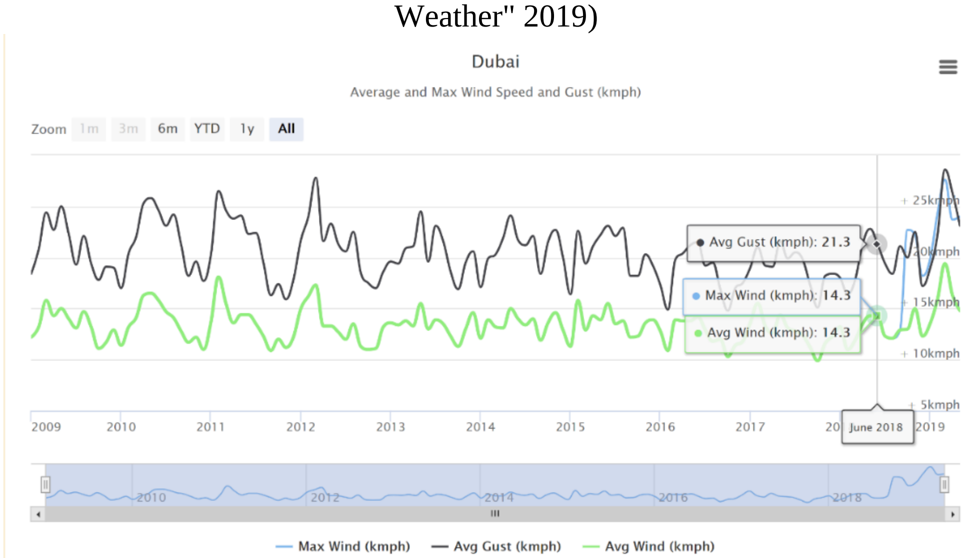


Figure 40: Average and maximum wind speed in June 2018 in Dubai, ("Dubai Historical Weather" 2019)

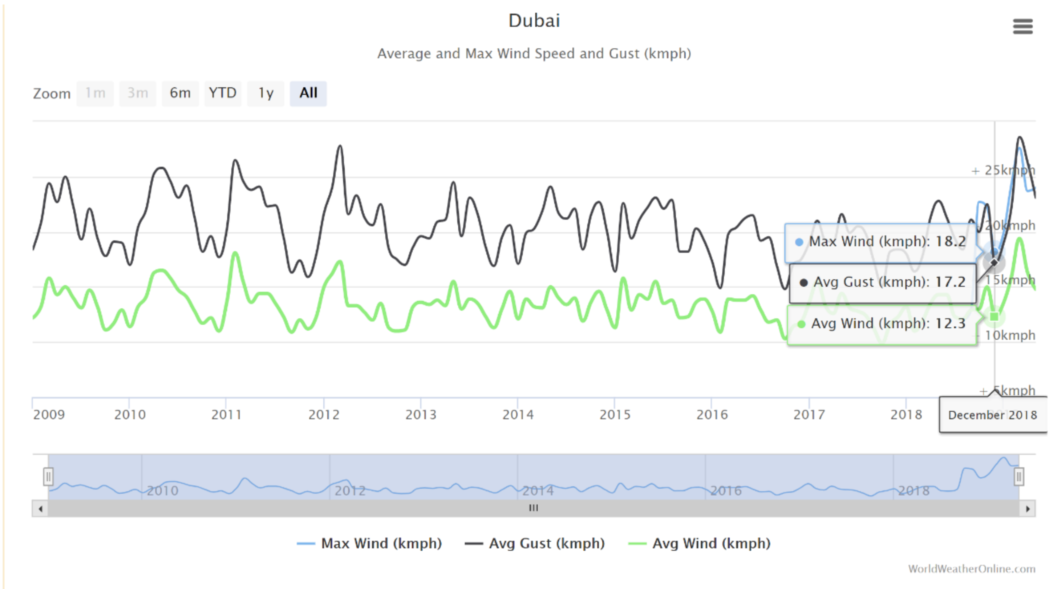


Figure 41: Average and maximum wind speed in December 2018 in Dubai, ("Dubai Historical Weather" 2019)

4.2.3 Construction Materials

Base case construction materials have been inserted in IES VE software for Dubai Frame as identified in the drawings attached in Appendix A. The drawings of Dubai Frame were collated through Dubai Municipality as this research is proposed in corporation with their RND department.

Table 5 below indicates the materials assigned for external walls, Roof and external windows that was used to validate IES VE model and assess the impact of kinetic façade systems on the building. Moreover, materials specifications, thickness and thermal conductivity are explained to achieve the same U value of the building envelop in reference to the drawings submitted for construction.

Table 5: Base Case Construction Materials

	Total Thickness (mm)	**Total U-value (W/m2K)**	**Construction layers (outside to inside)**	**Thickness (mm)**	**Thermal conductivity (W/m.K)**
External walls	420	0.49	Copper	5	200
			Cavity	45	-
			Expanded polystyrene	50	0.035
			Reinforced Concrete	300	2.3
			Plaster (light weight)	20	0.16
External windows	42	1.6	Outer pane	6	1.06
			Cavity	12	-
			Inner pane	6	1.06
			Cavity	12	-
			Inner Pane	6	1.06
Roof	450	0.30	Copper	5	200
			Cavity	45	-
			Expanded polystyrene	100	0.035
			Membrane	0.1	1
			Reinforced Concrete	300	2.3

4.3 IES VE software Validation

Previous studies have validated the use of IES VE software to conduct simulation of kinetic systems, (Loonen et al. 2016) (El Geresi & Abu Hijleh 2011) (Elzeyadi 2017). However, in this case of study, IES VE software was used to validate on-site measurements of one of Dubai Municipality buildings in order to accredit the software for Dubai Green Building evaluation system (Sa'fat).

Therefore, energy bills for six months were collated and field measurements of daylighting levels (lux levels) were conducted using an environmental meter provided by EXTECH instruments on the 9th of February 2019 for three timings; 12 PM, 3 PM and 6 PM.

The following sections describe the internal gains and electric lighting settings that were inserted in IES VE software. Moreover, base case construction materials, which were indicated in the previous section, were used in modelling the building to comply with existing case study conditions. ApacheSim application was used for conducting cooling and electricity consumption levels to be compared with actual energy bills and real climate conditions that is applied using AP-Locate built-in application.

4.3.1 Internal heat gains

There are two types of cooling loads that affect the amount of energy used by HVAC systems for the purpose of maintaining indoor air temperature: sensible cooling loads and latent cooling load. Latent cooling load can be identified based on the amount of people entering the building, equipment and appliances such as escalators and elevators, (Ashrae. 2013). In this case study internal heat gains (IHG) include, (Thomas 2019):

1. People that would be a source of sensible and latent heat gain.
2. Lights which is only considered as sensible heat gain
3. Escalators and elevators, which are categorized under electrical plug loads that falls under sensible heat gains.

The building has two elevators and one escalator as indicated in the floor plans in Appendix A. Therefore, based on the data conducted from ANSI/ASHRAE/IES Standard 90.1-2016, Performance Rating Method Reference Manual, elevators and escalator account for 3% to 5% of the total electricity usage in the building, (Pacific NorthWest National Laboratory 2017).

Furthermore. The building has approximately 26 screens with an average approximate dimension of 2x1 M, (Operation Team 2019). Table 6 indicates the influence of heat gains according to ASHRAE calculations of screens and monitors, (Ashrae. 2013).

Table 6: Monitors heat gains based on ASHRAE calculations, (Ashrae. 2013).

Appliance	**Heat gains**	
	Continuous (W)	**Energy Saver Mode (W)**
Small monitor (330 to 380 mm)	55	0
Medium monitor (400 to 460 mm)	70	0
Large monitor (480 to 510 mm)	80	0

As the building is considered a touristic landmark in Dubai, User profile details for the visitors were collated from the operation team who mentioned that usually Dubai Frame accept 5000 visitors in Weekends (Saturday and Friday) and 3000 visitors on Thursdays. However, in normal days the number of visitors ranges from 500 to 1000 people. It should be also noted that the staff of the operation team ranges from 7 to 15, which might vary, based on the load required for staffing. On the other hand, it should be noted that the existing HVAC system operates for 24 hours, (Operation Team 2019).

4.3.2 Electric Lighting

In IES VE, electric lighting has been inserted in the default settings of IES VE; illuminance levels were logged as 500 lux whereas the limiting glare index was 19. Working surface height was indicated as 0.85 m and mounted on 2.7 whereas both LMF and RSMF were put as 0.9. Figure 42 below shows the default general lighting and lighting luminaries as inserted in the building template manager for the proposed case study.

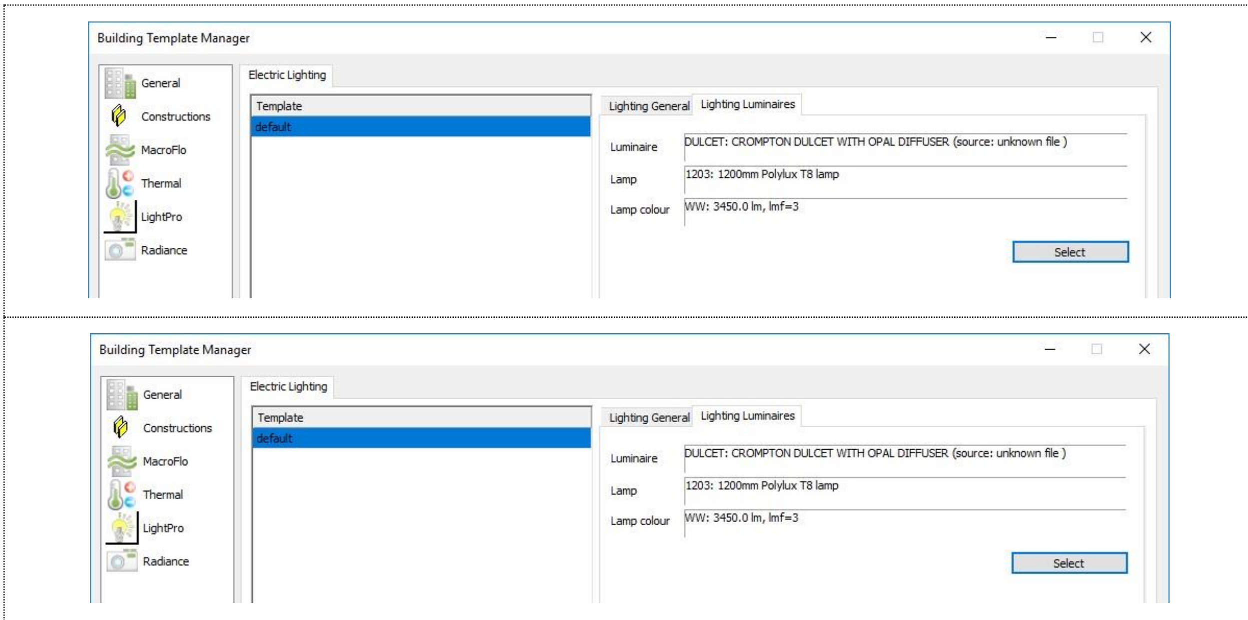


Figure 42: Base case electric lighting default setting in IES VE

4.3.3 Energy Consumption validation

The main aspect for validating IES VE software in the selected case of study in this research is the energy consumption levels. The data of energy consumption was collated from Dubai municipality maintenance department for six months from May to October as indicated in the table below. Table 7 lists the energy consumption of two meters connected to the building with an indication of DEWA bill monthly cost, (Uddin, M. 2019, pers. comm.)

Table 7: Energy consumption and bills of Dubai Frame for six months

Month	Meter 01 (KWH)	Meter 02 (KWH)	Total Consumption	Total Cost	VAT
May	146,338	148,596	294.934	130126.9	6506.34
June	149,083	146,160	295.243	130,263.23	6513.16
July	176,854	148,596	325.45	143,705.07	7185.25
August	199,265	155,904	355.169	156930.11	7846.50
September	182,213	151,032	333.245	147173.93	7358.69
October	146,647	147,134	239.781	128732.82	6436.64

After inserting the internal gains and the default lighting setting as mentioned above, a simulation for the base case model was conducted through IES VE software. The building and the façade pattern were modelled in IES VE in reference to the base case construction materials and UAE climatic conditions.

Table 8 shows a comparison between the actual energy bills and the results obtained from the base case simulation through IES VE. The discrepancy between actual and simulated data ranges between 2.9% to 6.5% with an average of 4.7% as described in Figure 43.

Table 8: Actual energy consumption validation

Month	Actual Energy Bills-. (MWH)	IES VE- Total Electricity (MWH)	IES VE Room cooling plants (MWH)	Validation Discrepancy
January	-	240.863	430.4836	-
February	-	232.122	417.9595	-
March	-	263.407	475.5708	-
April	-	277.783	505.9753	-
May	294,934	312.015	572.7881	-5.8%
June	295.243	314.416	579.243	-6.5%
July	325.45	334.864	618.4854	-2.9%
August	355.169	337.831	624.4189	4.9%
September	333.245	317.216	584.8426	4.8%
October	239.781	307.626	564.0157	-4.7%
November	-	272.251	494.9125	-
December	-	252.338	453.4321	-
Total	-	3462.74	6322.1274	-

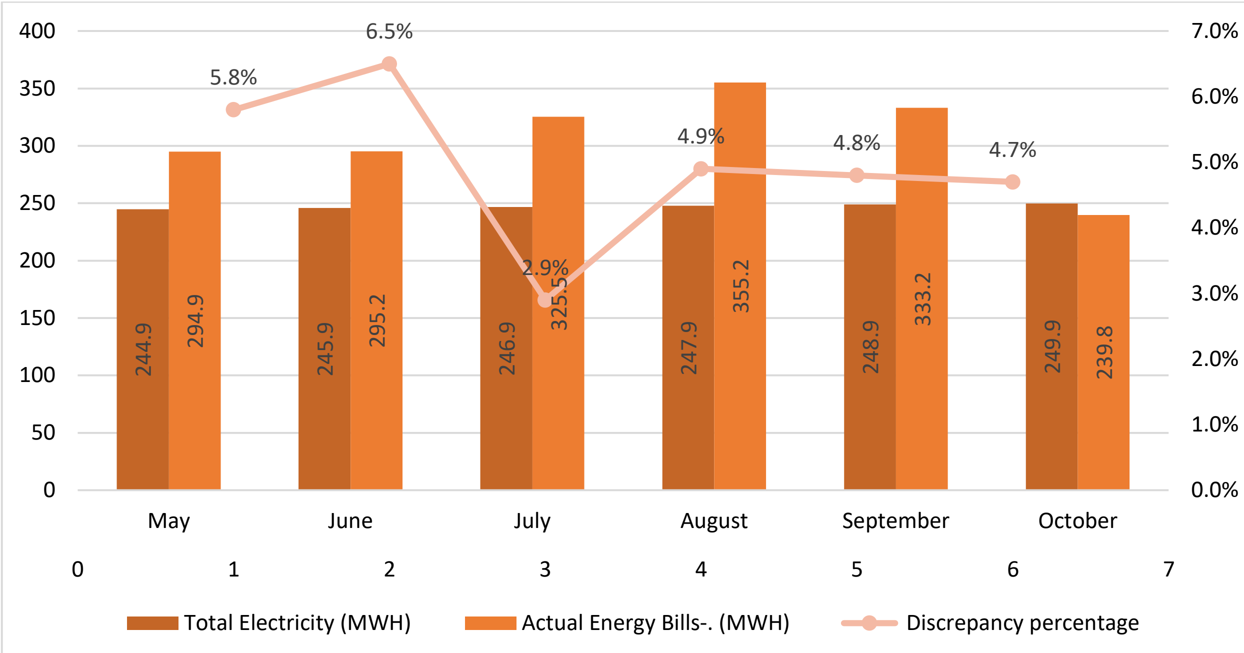


Figure 43: Total electricity validation and discrepancy percentage

4.3.4 Daylighting validation

Daylighting levels were measured using an environmental meter provided by EXTECH instruments on the 9th of February 2019 for three timings; 12 PM, 3 PM and 6 PM. This instrument measures temperature, RH and daylighting levels. However, RH and temperature figures were neglected as the building has an HVAC system that automatically operates for 24 hours on a set point for temperature and RH. Moreover, daylighting levels that were conducted at 6:00 PM were neglected as the sunset was at 6:09 PM on that day.

During the site visit, daylighting measures were taken in two areas; the Mezzanine Floor and the Viewing Bridge from both East and West sides at 12:00 PM and 15:00 PM. Table 10. 11 and 12 show a comparison between data conducted on site and data generated from IES VE software presented in luminance and radiance contour images. On the other hand, Table 13 shows the discrepancy between data conducted on site and an average of three points indicated in the luminance images in each side of the building.

Table 9: Mezzanine Floor luminance and radiance contour images at 12:00 PM

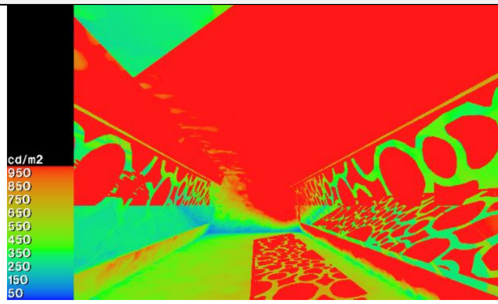
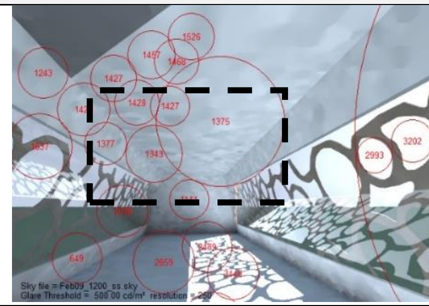
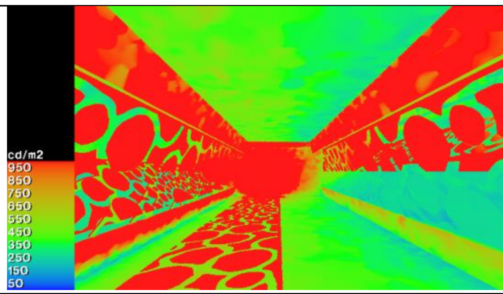
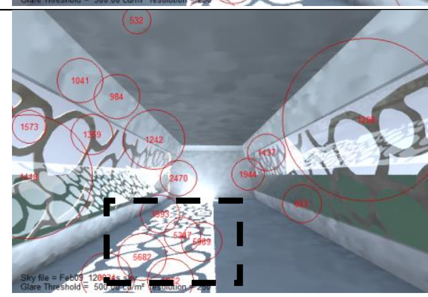
Side	Daylight Simulation- IES VE		Field (lux)
	Radiance Contour Images	Luminance Images	
East			
West			

Table 10: Mezzanine Floor luminance and radiance contour images at 15:00 PM

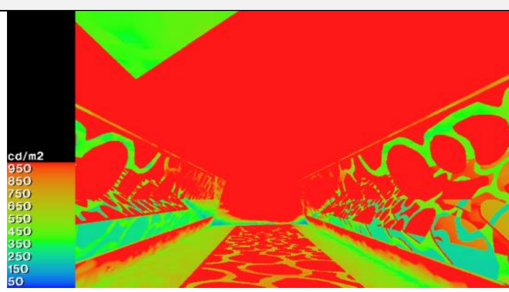
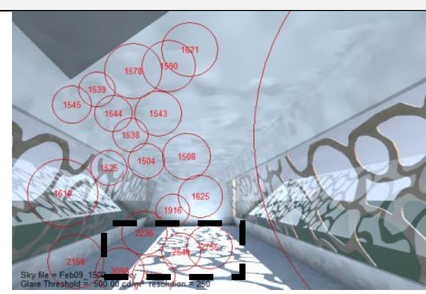
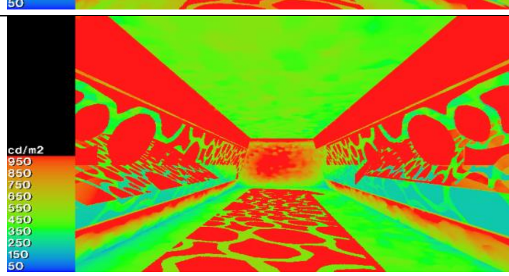
Side	Daylight Simulation- IES VE		Field (lux)
	Radiance Contour Images	Luminance Images	
East			
West			

Table 11: Viewing Bridge luminance and radiance contour images at 12:00 PM

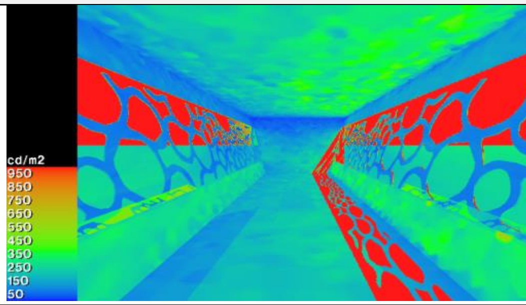
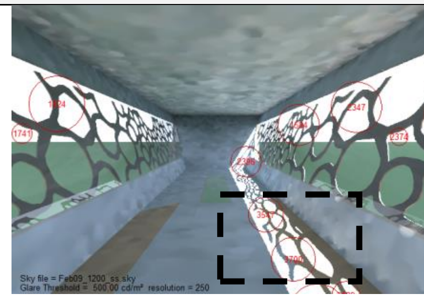
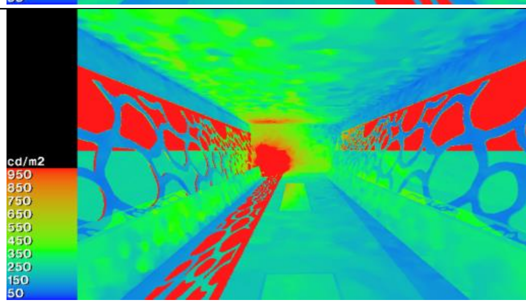
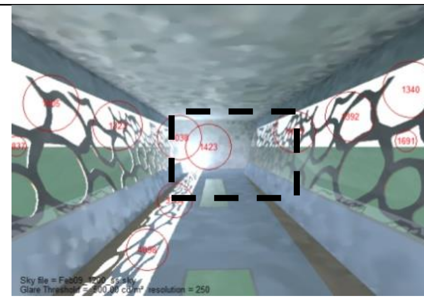
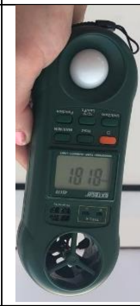
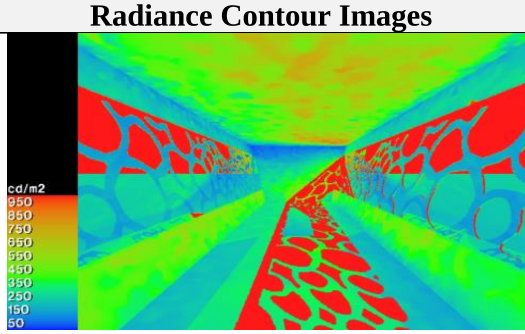
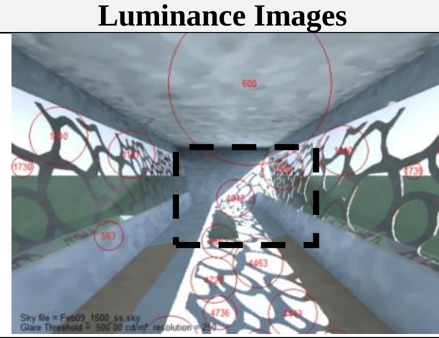
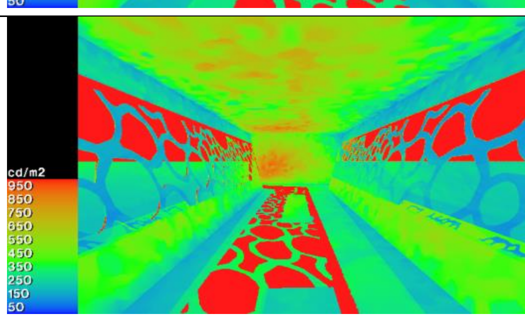
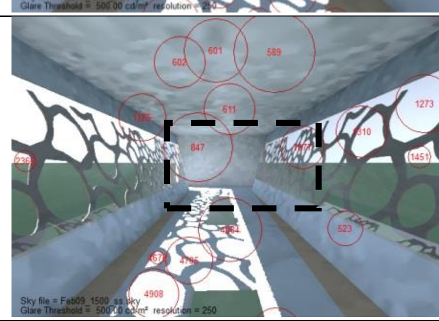
Side	Daylight Simulation- IES VE		Field (lux)
	Radiance Contour Images	Luminance Images	
East			
West			

Table 12: Viewing Bridge luminance and radiance contour images at 15:00 PM

Side	Daylight Simulation - IES VE		Field (lux)
	Radiance Contour Images	Luminance Images	
East			
West			

The discrepancy percentage between IES VE result and the data conducted in the field measurements for luminance levels ranges from 0.79% to 6.64% with an average discrepancy of 2% as shown in Figure 44, which validate the use of IES VE software for daylight simulation.

Table 13: The discrepancy of luminance levels between IES VE results and field measurements

Location/ Time		IES VE - Luminance levels (Lux)				Field measurements	Discrepancy Percentage
		Point 1	Point 2	Point 3	AVE		
Mezzanine Floor	12:00 PM East	1375	1427	1428	1410	1423	-0.92%
	12: 00 PM West	5989	5347	3993	5109.6	5150	-0.79%
	15:00 PM East	3419	2755	3098	3090.6	3040	1.64%
	15:00 PM West	794	4479	2124	2465.6	2480	-0.58%
Viewing Bridge	12:00 PM East	2395	3547	3700	3214	3390	-5.48%
	12: 00 PM West	3164	1423	1038	1875	1818	3.04%
	15:00 PM East	4043	1530	4562	3378.3	3580	-5.97%
	15:00 PM West	847	4984	1877	2569.3	2740	-6.64%

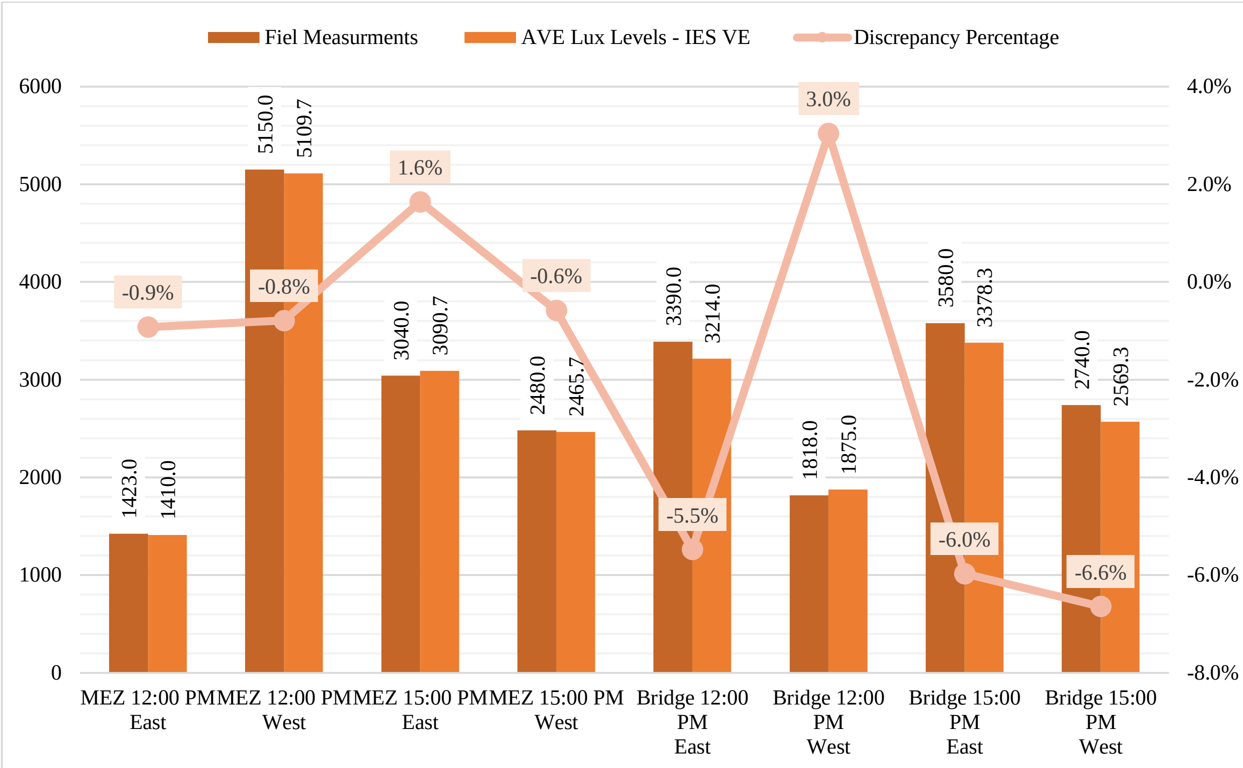


Figure 44: Total daylight validation measures

4.4 Base case simulation

The results of the base case scenario were generated with the existing fixed shading. It should be noted that the existing HVAC system was assumed to be automatically operated for 24/7 as indicated by Dubai Frame operation team, (Operation Team 2019).

Energy consumption and daylighting figures were generated for three days of the year; March 21st, June 21st and December 21st. The three days cover all seasons and should be sufficient to give an indication of the building performance during the whole year to be compared with the proposed kinetic system performance in the next chapter. These scenarios will be named in reference to Table 14 below.

Table 14: The proposed simulation scenarios’ date and time

Simulation Scenarios	Date	Time
SIM 1	March 21st	08:30 AM
SIM 2	March 21st	12:30 PM
SIM 3	March 21st	17:30 PM
SIM 4	June 21st	08:30 AM
SIM 5	June 21st	12:30 PM
SIM 6	June 21st	17:30 PM
SIM 7	December 21st	08:30 AM
SIM 8	December 21st	12:30 PM
SIM 9	December 21st	17:30 PM

Figure 45 illustrates the base case total electricity and cooling loads of SIM 1-9. The highest loads are shown in SIM 5 (June 21st at 12:30 PM) whereas the lowest loads are presented in SIM 7 (June 21st at 12:30 PM). On the other hand, Figure 46 describes the total electricity and cooling loads of the base case over the year.

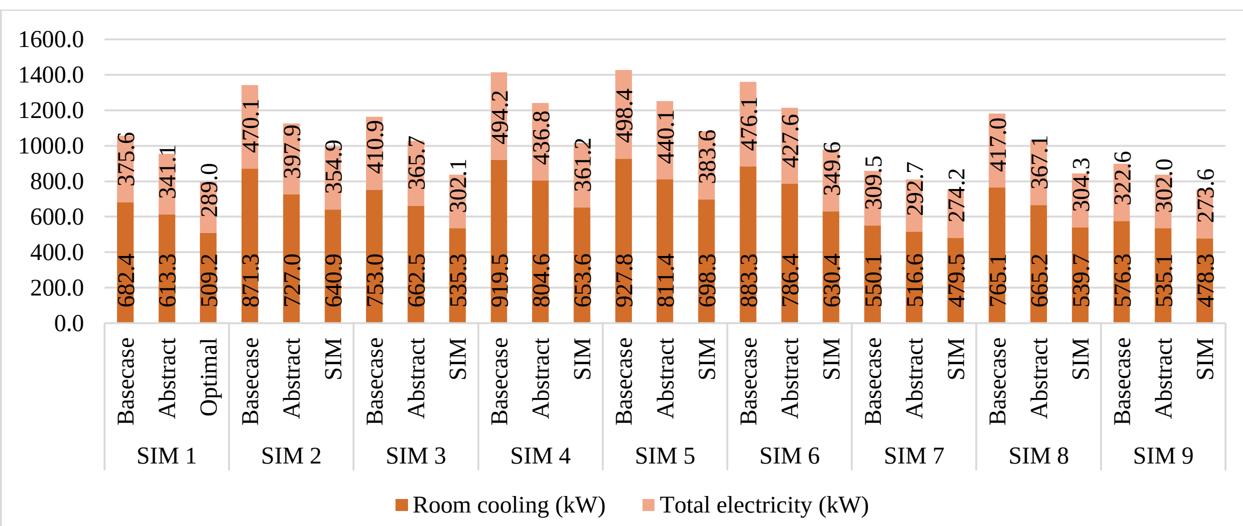


Figure 45: Base case total electricity & cooling loads of SIM 1-9

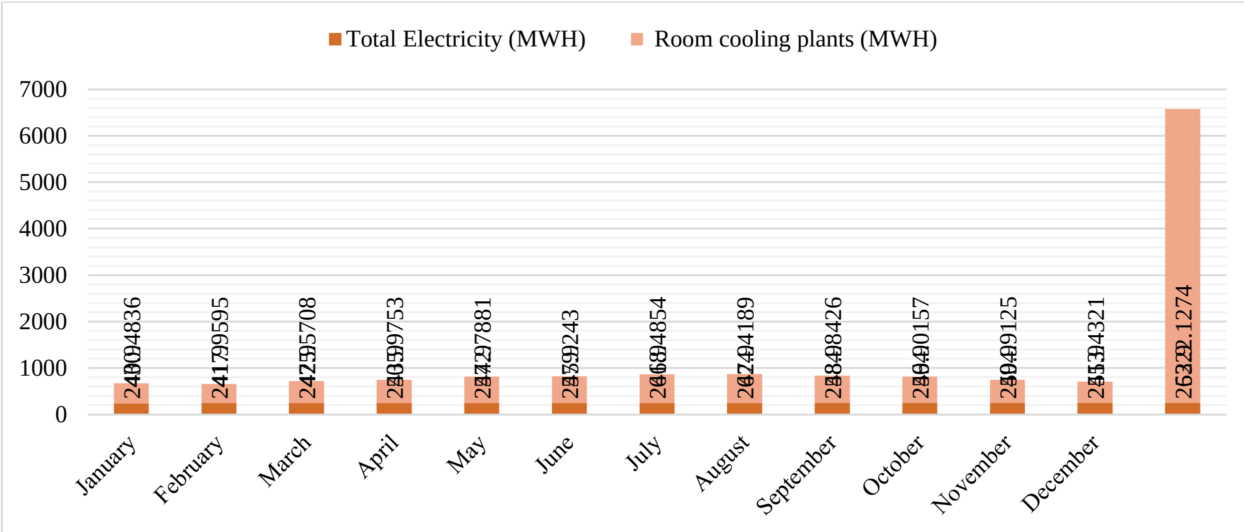


Figure 46: Base case total electricity & cooling loads over the year

In addition, Table 15 describes the base case luminance and radiance contour images of SIM 1-9. The analysis of luminance results is conducted by taking an average of three points located in both East and West side for each scenario in the Viewing Bridge and the Mezzanine Floor as indicated Table 16 and Table 17. The locations of these measurements are described in Figure 47.

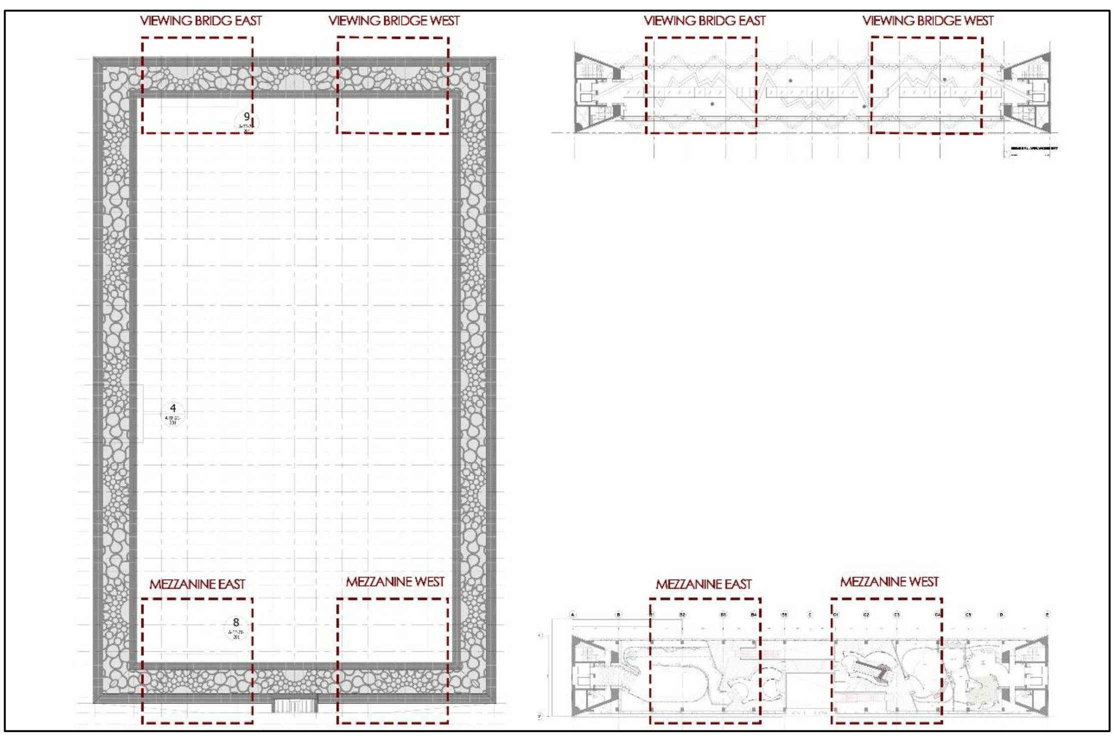
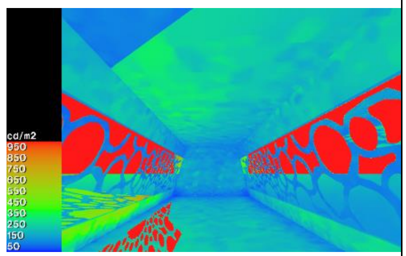
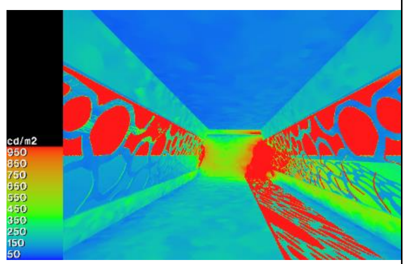
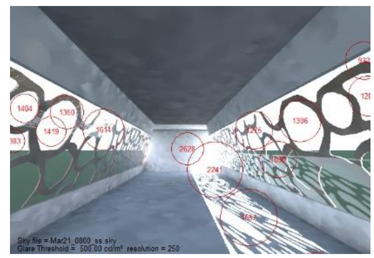
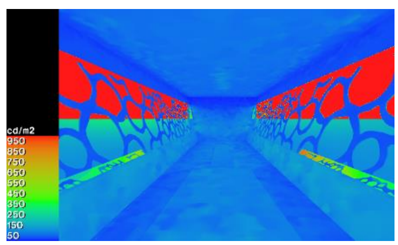
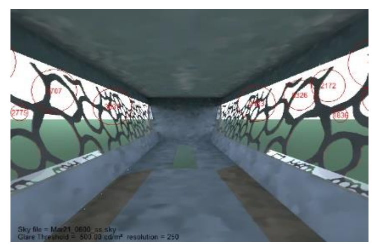
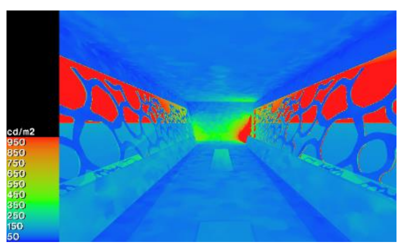
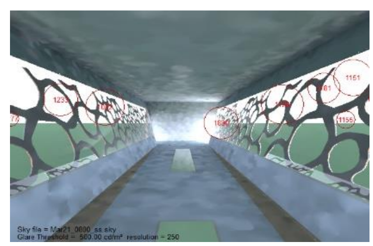
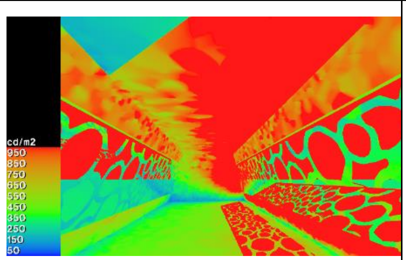
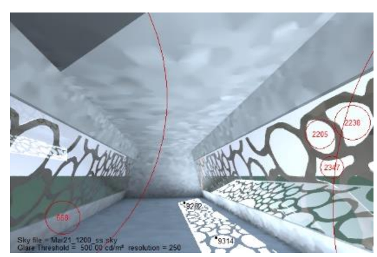
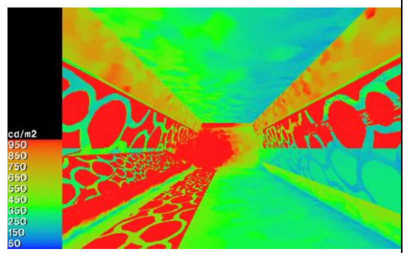
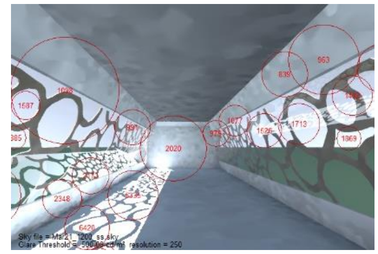
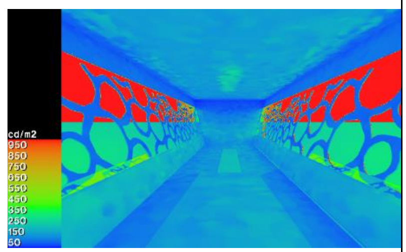
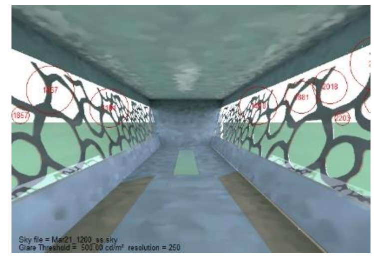
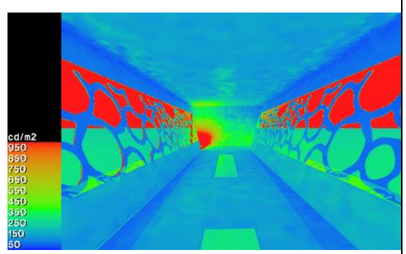
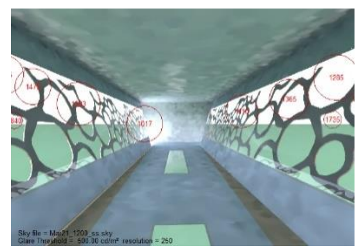
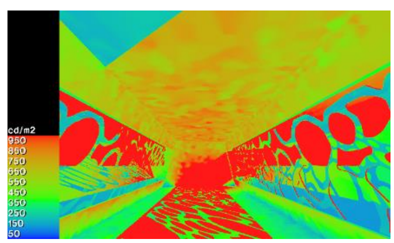
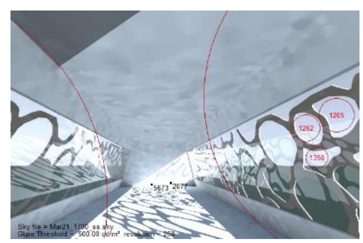
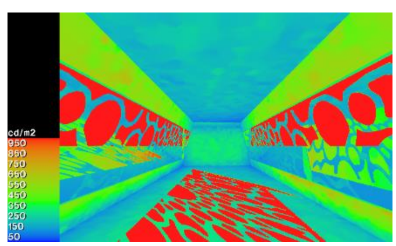
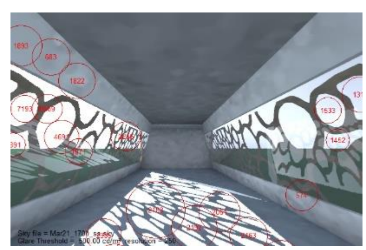
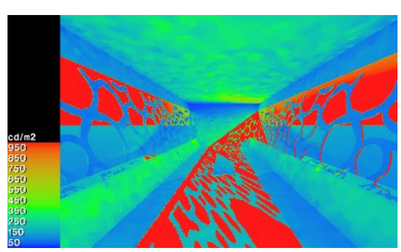
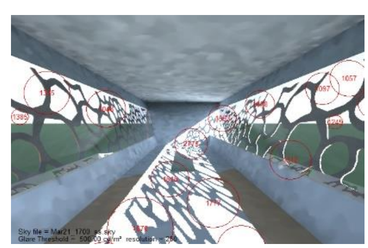
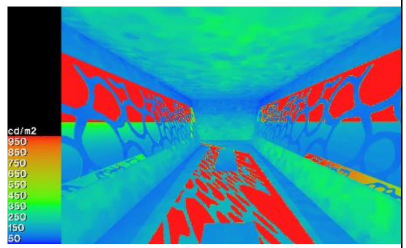
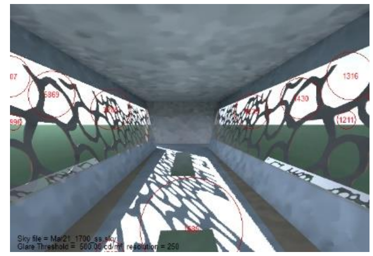
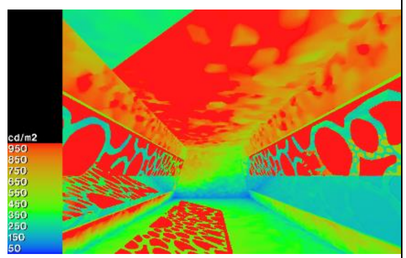
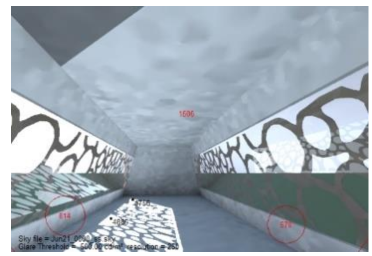
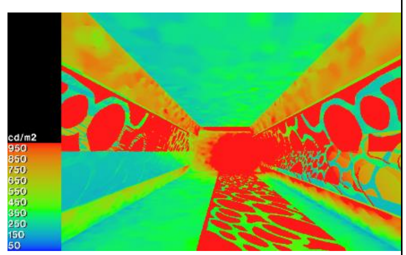
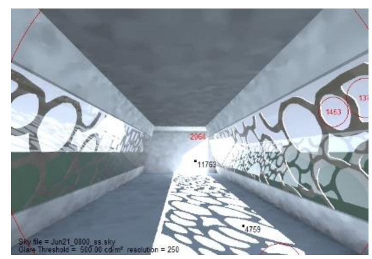
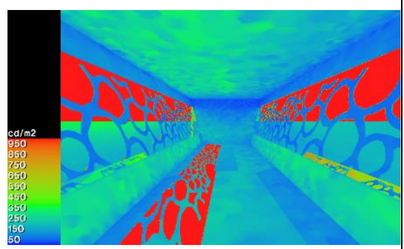
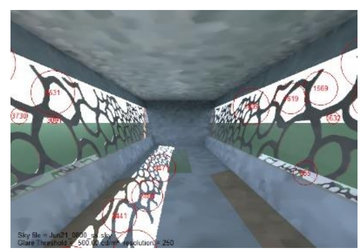
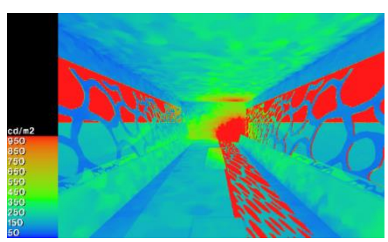
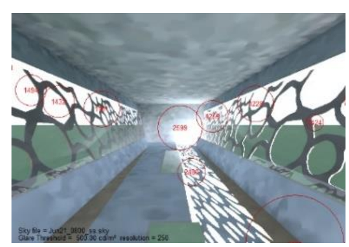
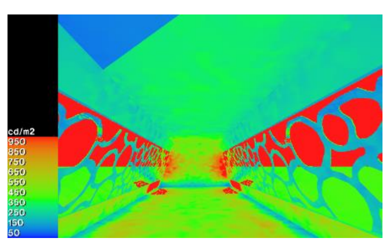
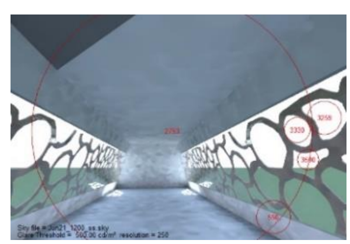


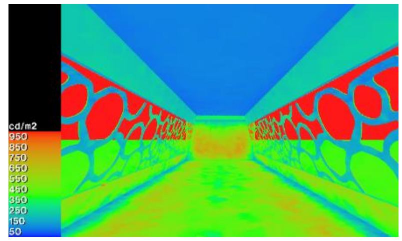
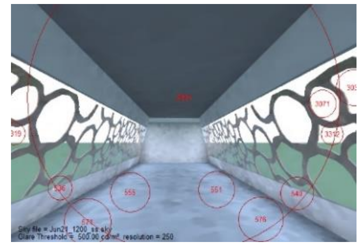
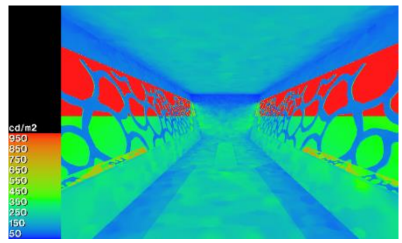
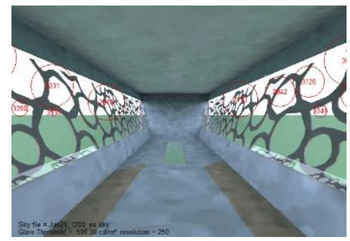
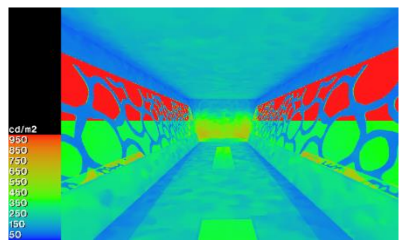
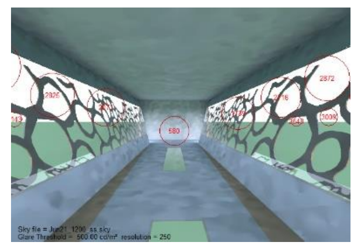
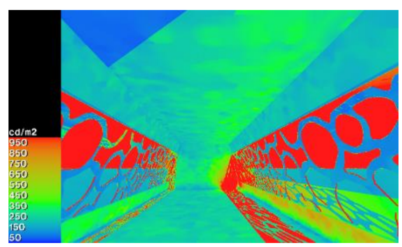
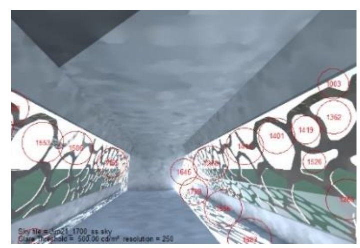
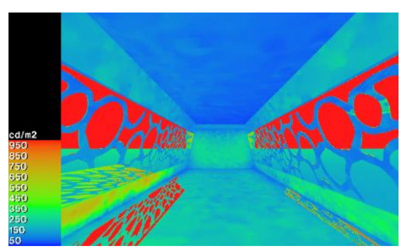
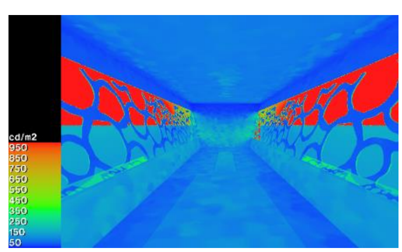
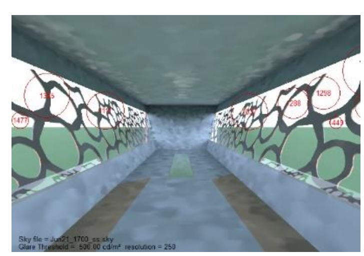
Figure 47: Dubai Frame field measurements locations

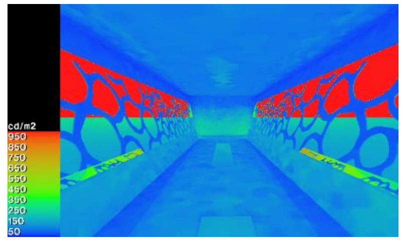
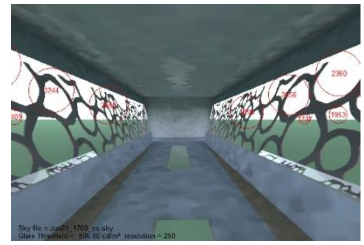
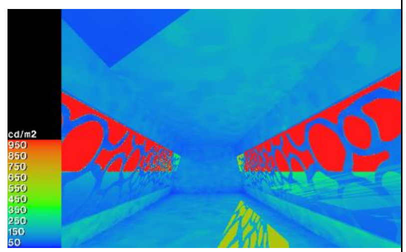
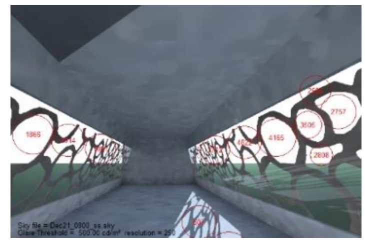
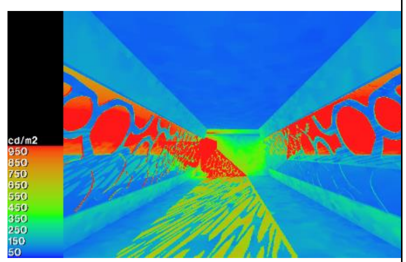
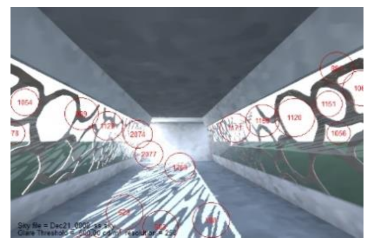
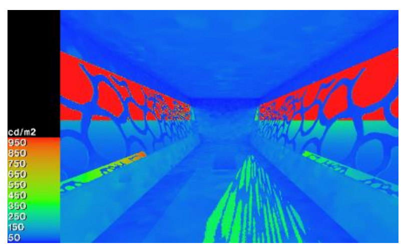
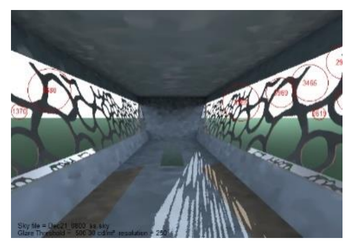
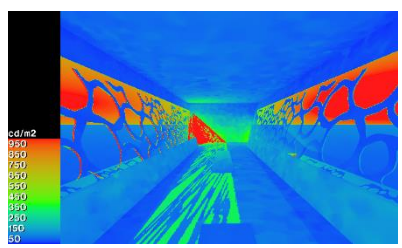
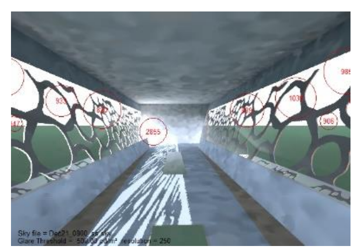
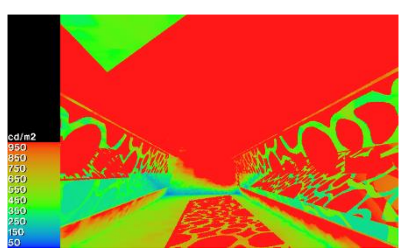
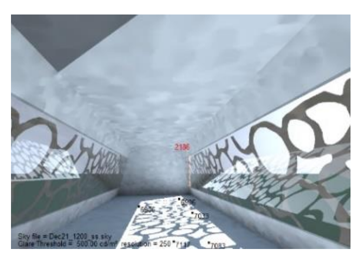
Table 15: Base case luminance and radiance contour images of SIM 1-9

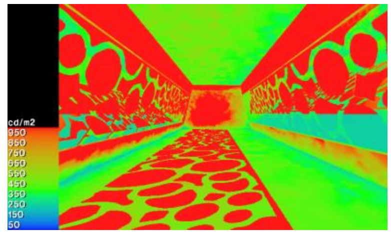
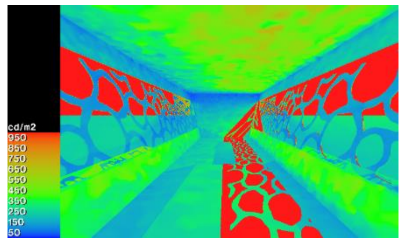
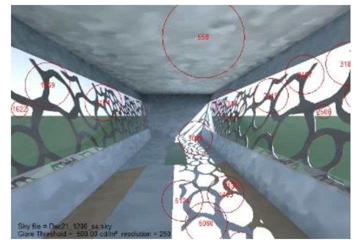
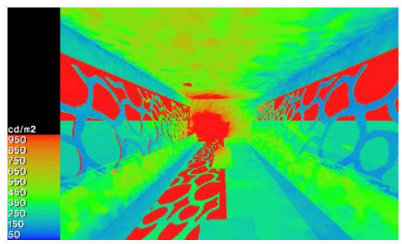
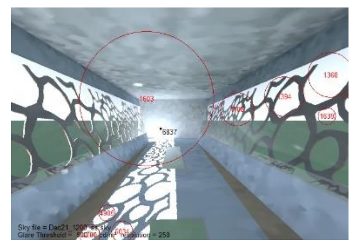
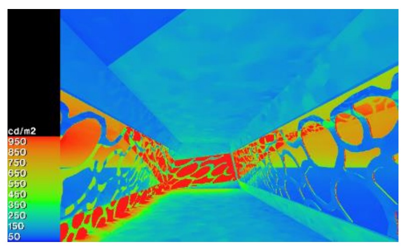
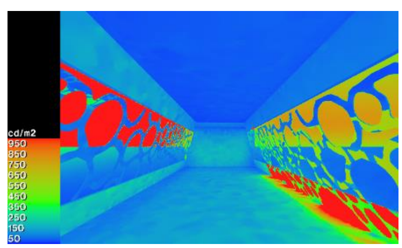
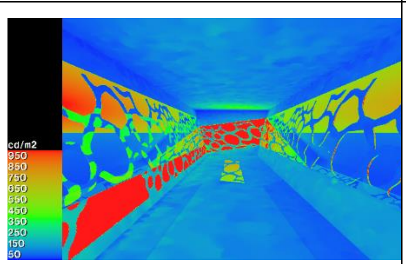
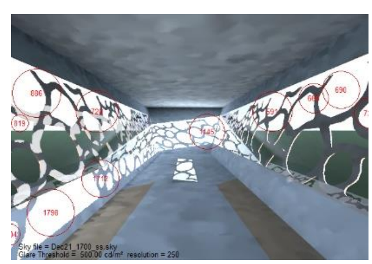
Base case Scenarios	Location		Radiance Contour Images	Luminance Images
SIM 1	Mezzanine Floor	East		
		West		
	Viewing Bridge	East		
		West		
SIM 2	Mezzanine Floor	East		

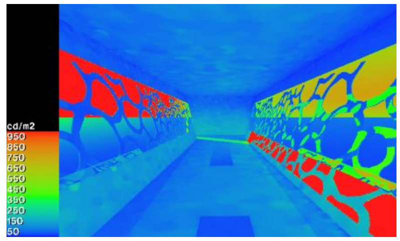
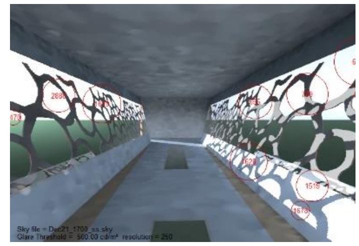
		West		
	Viewing Bridge	East		
		West		
SIM 3	Mezzanine Floor	East		
		West		
	Viewing Bridge	East		

		West		
SIM 4	Mezzanine Floor	East		
		West		
	Viewing Bridge	East		
		West		
SIM 5	Mezzanine Floor	East		

		West		
	Viewing Bridge	East		
		West		
SIM 6	Mezzanine Floor	East		
		West		
	Viewing Bridge	East		

		West		
SIM 7	Mezzanine Floor	East		
		West		
	Viewing Bridge	East		
		West		
SIM 8	Mezzanine Floor	East		

		West		
	Viewing Bridge	East		
		West		
SIM 9	Mezzanine Floor	East		
		West		
	Viewing Bridge	East		

		West		

The highest luminance levels in the East side are shown in SIM 8 for the Mezzanine Floor and the Viewing Bridge. The average luminance levels in the Mezzanine are 7007.3 lux and 4882.3 lux in the Viewing Bridge. On the other hand, in the West side, SIM 4 with an average of 5991.7 lux is the highest in the Mezzanine Floor whereas SIM 8 with an average of 4448.3 lux is the highest in the Viewing Bridge.

Figure 48 shows the average base case luminance levels of SIM 1-9 in the East Side. However, Figure 49 illustrates the average base case luminance levels of SIM 1-9 in the West Side.

Table 16: Base case luminance levels of SIM 1-9/ East Side

	Location	Point 1	Point 2	Point 3	AVE Luminance Levels
SIM 1	**Mezzanine Floor**	2480	1788	4121	2796.3
	Viewing Bridge	2172	2775	3707	2884.7
SIM 2	**Mezzanine Floor**	2205	2347	9314	4622.0
	Viewing Bridge	1857	2018	2203	2026.0
SIM 3	**Mezzanine Floor**	1262	2077	5673	3004.0
	Viewing Bridge	1777	2775	1818	2123.3
SIM 4	**Mezzanine Floor**	1506	5756	4860	4040.7
	Viewing Bridge	2141	2468	2471	2360.0
SIM 5	**Mezzanine Floor**	2753	550	3330	2211.0
	Viewing Bridge	3120	2942	2031	2697.7
SIM 6	**Mezzanine Floor**	1553	1645	1799	1665.7
	Viewing Bridge	1365	1288	1477	1376.7
SIM 7	**Mezzanine Floor**	4165	1866	607	2212.7
	Viewing Bridge	1370	3465	2619	2484.7
SIM 8	**Mezzanine Floor**	7033	6906	7083	7007.3
	Viewing Bridge	5124	5060	4463	4882.3
SIM 9	**Mezzanine Floor**	2198	1527	757	1494.0
	Viewing Bridge	1798	1145	1712	1551.7

Table 17: Base case luminance levels of SIM 1-9/ West Side

	Location	Point 1	Point 2	Point 3	AVE Luminance Levels
SIM 1	**Mezzanine Floor**	2628	2241	1637	2168.7
	Viewing Bridge	1151	1830	1233	1404.7
SIM 2	**Mezzanine Floor**	2020	979	6420	3139.7
	Viewing Bridge	1017	1365	1285	1222.3
SIM 3	**Mezzanine Floor**	2064	2152	2162	2126.0
	Viewing Bridge	1530	1430	5869	2943.0
SIM 4	**Mezzanine Floor**	11763	4759	1453	5991.7
	Viewing Bridge	2599	2480	1269	2116.0
SIM 5	**Mezzanine Floor**	555	551	576	560.7
	Viewing Bridge	580	2872	2825	2092.3
SIM 6	**Mezzanine Floor**	3619	2827	2031	2825.7
	Viewing Bridge	3244	2360	3244	2949.3
SIM 7	**Mezzanine Floor**	628	1259	2077	1321.3
	Viewing Bridge	2855	1039	933	1609.0
SIM 8	**Mezzanine Floor**	7301	2820	517	3546.0
	Viewing Bridge	6837	1603	4905	4448.3
SIM 9	**Mezzanine Floor**	1796	1732	4472	2666.7
	Viewing Bridge	2880	1628	1519	2009.0

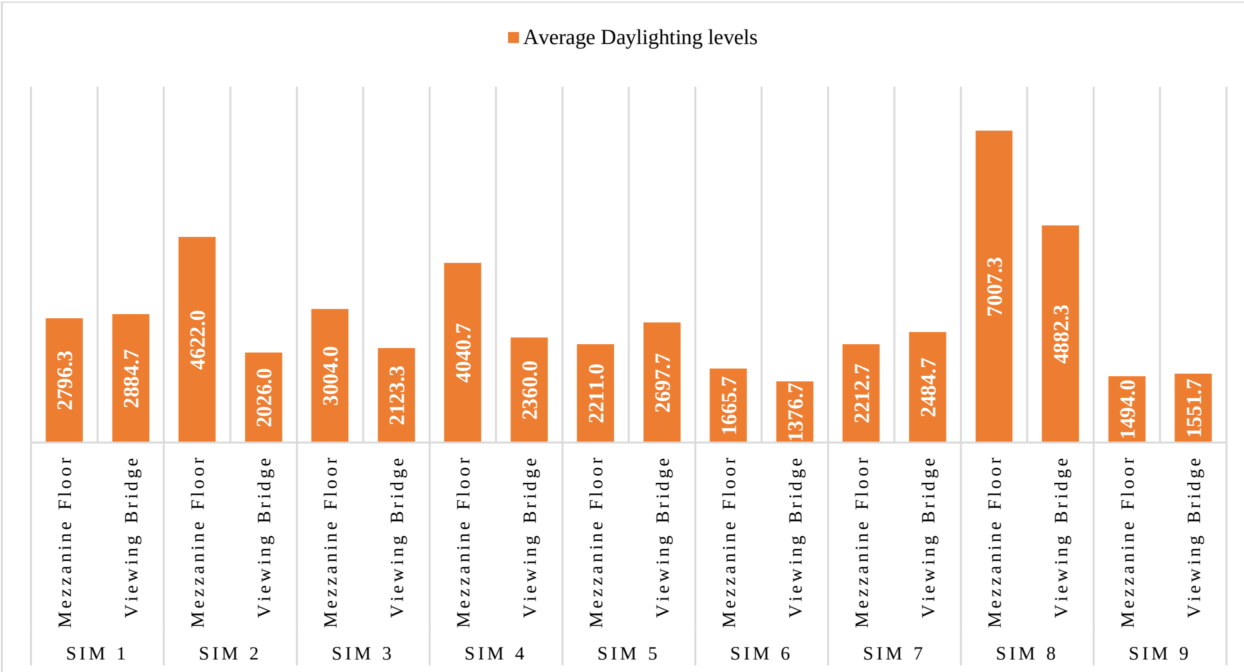


Figure 48: Base case luminance levels of SIM 1-9/ East Side

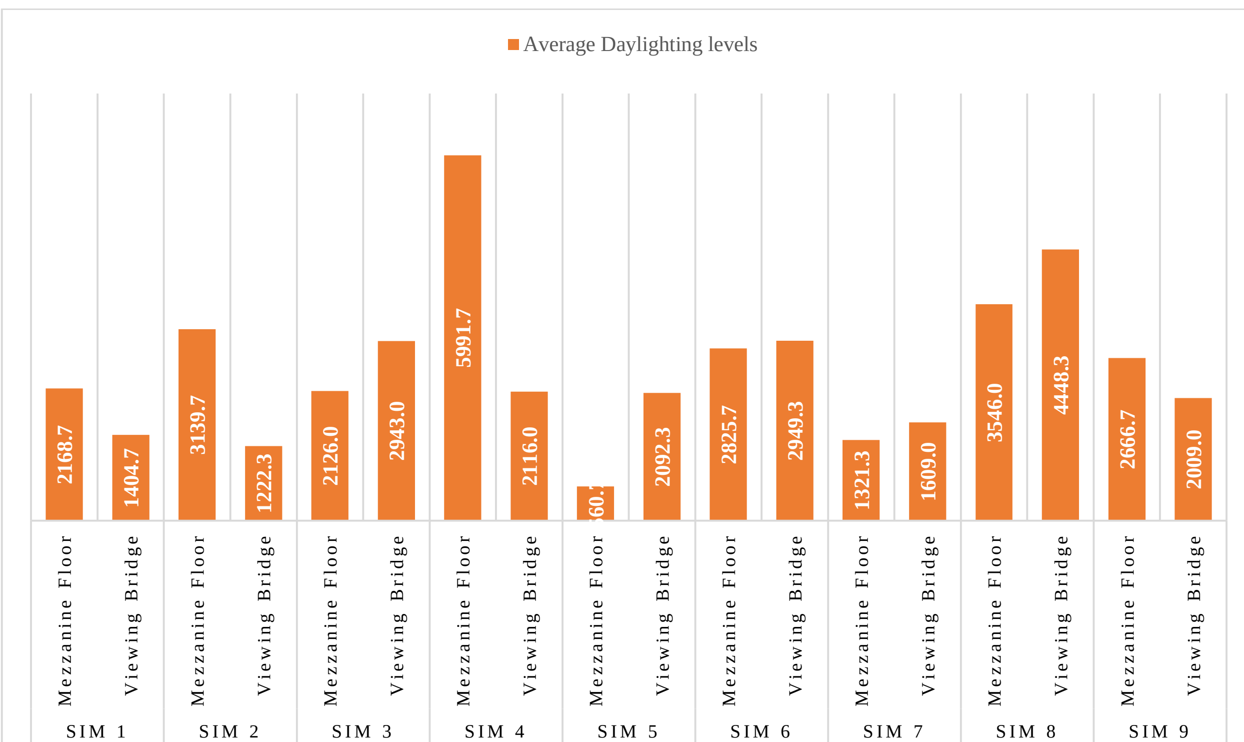


Figure 49: Base case luminance levels of SIM 1-9/ West Side

4.5 Kinetic System Design Development

The design development of the proposed façade went into three phases; the first one is collecting information of the environment that was explained in the site analysis and climatic figures of the case study. The second phase is to process the information of the building technical figures, functionality and the concept of the design to end up with the last phase of taking actions and developing a kinetic façade and its movement mechanism.

4.5.1 Stage one: Selecting the kinetic system

The first stage of developing kinetic façade of Dubai Frame building starts by selecting the appropriate kinetic system of the building. Therefore, five parameters were taking into consideration that can be identified as follows:

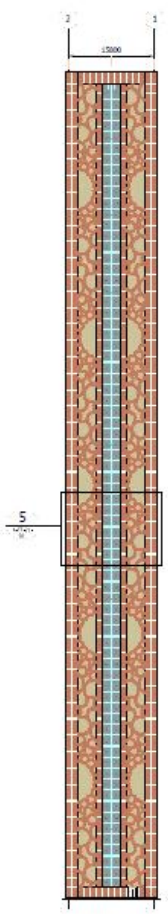
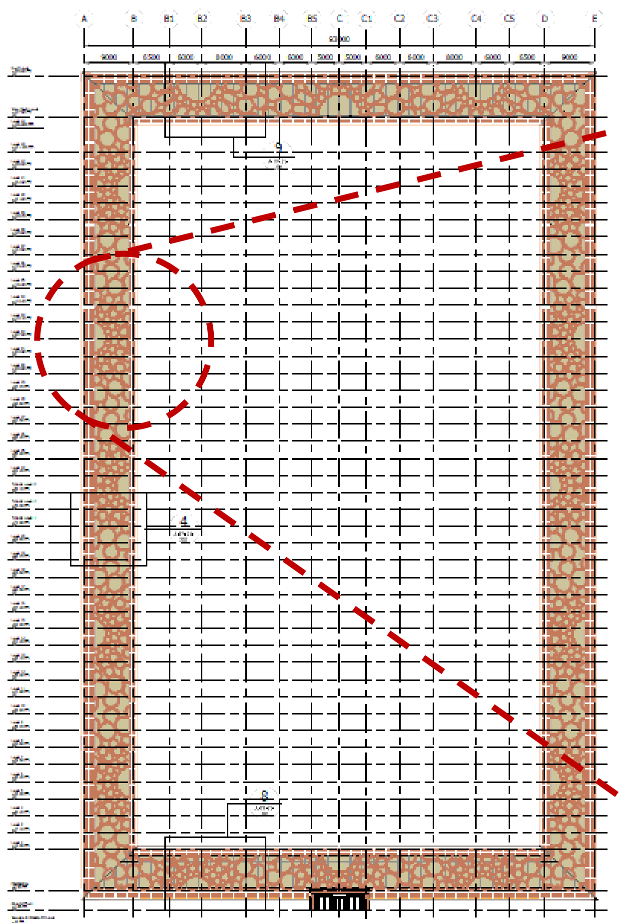
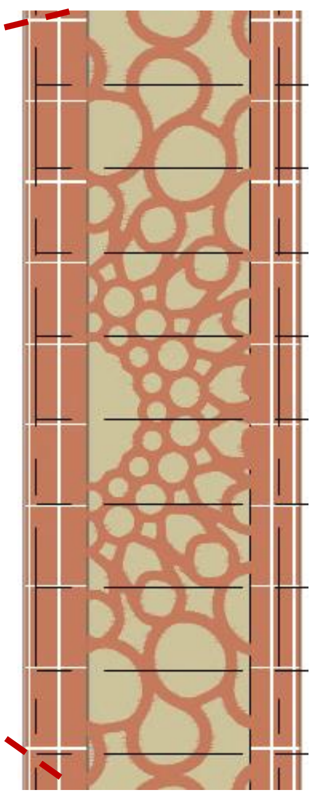
1. The façade shape and pattern that was inspired by an important factor, which is shape of a ring collected from an archaeological site in Dubai as explained earlier.
2. The movement that can be applied on this pattern, which relates to geometric shapes typology.
3. To select a kinetic system that can be realistically applied on the building.
4. To achieve the targeted energy reduction levels of kinetic systems as indicated in the LR.
5. To respect the functionality and the concept of the building which is positioned to overlook the new Dubai from one side and the old city from the other side

4.5.2 Stage two: Selecting the kinetic typology

In reference to the proposed kinetic system, parameters that are listed in stage one; a study was made on how to propose a kinetic movement for this system. Based on the literature, the typology the can be selected falls under automated movable screens, 3D geometric screens typology, which results in 38% energy savings and depends on the screen pattern, geometry depth operability, material and solid to void ratio, (Elzeyadi 2017).

Dubai Frame façade pattern is a combination of a repetitive unit mirrored and rotated to create the configuration described below, which is inspired from Expo logo and placed in a solid steel gold frame in both North and South façade. However, in East and West façade, the pattern is only displayed in front of the solid part and glazing windows are placed in its rectangular shape as shown in Table 18 below.

Table 18: Dubai Frame Elevations

East and West façade	South and North façade	Repetitive Unit of the existing façade pattern
		

To convert the existing fixed shading system to a kinetic system, an abstract is made to the façade to result in a more identified ornamental design components that can be based on mathematics and geometrics to create a variety of geometrical structures. In order to achieve this aim, a case study that implemented this typology, is used as an inspiration for this design, which is the Arabic Institute in Paris that was illustrated in the LR. Arabic institute façade was inspired from Mashrabiya and introduced kinetic geometry of Arabic patterns in square bays to create an innovative building, (Meagher 2015). The movement mechanisms of the geometric are displayed in Figure 50.

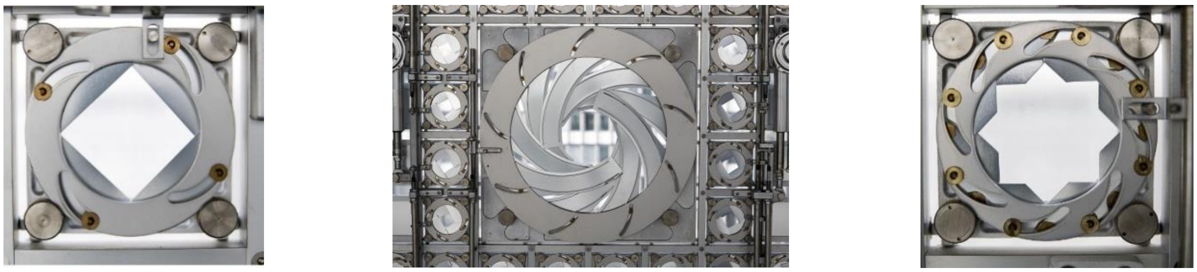
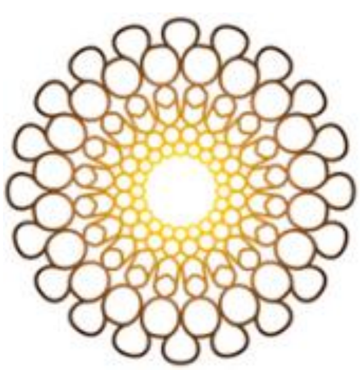
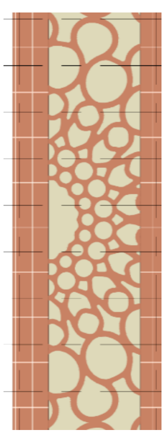
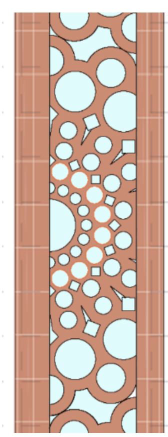


Figure 50: Arabic Institute movement mechanism, (Meagher 2015)

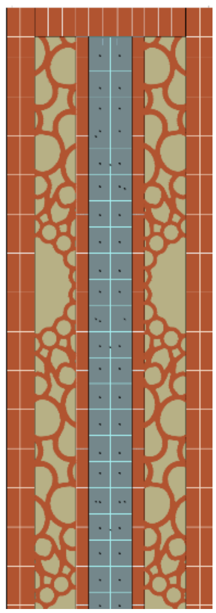
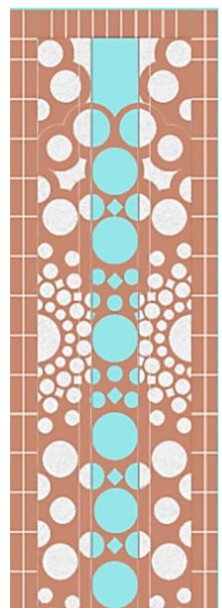
The design abstract is proposed to achieve the aims of the kinetic system and to keep the same look and feel of the building by respecting the concept of the existing design of the façade and to adopt with the proposed kinetic behaviour. Therefore, the current organic shapes are abstracted to geometric shapes, each shape will close and open based on a kinetic movement. Table 19 below explains the abstract of the proposed façade design configuration for South and North in reference to the existing pattern and Expo 2020 Dubai logo and with an inspiration of an indicative landscaping element of the building that was located in Dubai Frame plaza.

Table 19: Proposed façade design/ South and North facade

Reference Images		Existing pattern- Repetitive unit	Proposed Abstract- S/N façade- Repetitive unit
 Expo 2020 logo	 Landscaping elemnt located in Dubai Frame plaza		

On the other hand, Table 20 shows the proposed façade design of both East and West elevations that was designed to provide shading for the existing glazing of the panoramic elevator that link the Mezzanine with the Viewing Bridge of Dubai Frame. It should be noted that the existing fixed shading system is placed over solid walls and white mesh is used to act as a screen underneath the shading system.

Table 20: Proposed façade design/ East and West facade

Existing pattern	Proposed Abstract- E/W facade
	

4.5.3 Stage three: Selecting the kinetic mechanism

Selecting the kinetic movement of each shape will be identified in reference to Figure 9, Chapter 2 in Kinetic shading typologies where Nashaat et al. (2018) classified the kinetic movement to four main configurations; translation, rotation, scaling and material deformation. In this case study the classifications of the proposed kinetic movement fall under material deformation and scaling where the researcher proposed two types of material deformation; (i) Circles transferred to Islamic ornament, (ii) Circles transferred to an octagonal shape that would shape as a star while closing. On the other hand, scaling has been proposed to both circles and squares.

Table 21and Table 22 describe the exact location of the proposed kinetic behaviour with a description of the behaviour of the kinetic movement of the proposed geometrics. South and North façade share the same type of movement as shown in Table 21 and East façade acts the same as described in Table 22.

Table 21: Proposed kinetic movement/ South and North facade

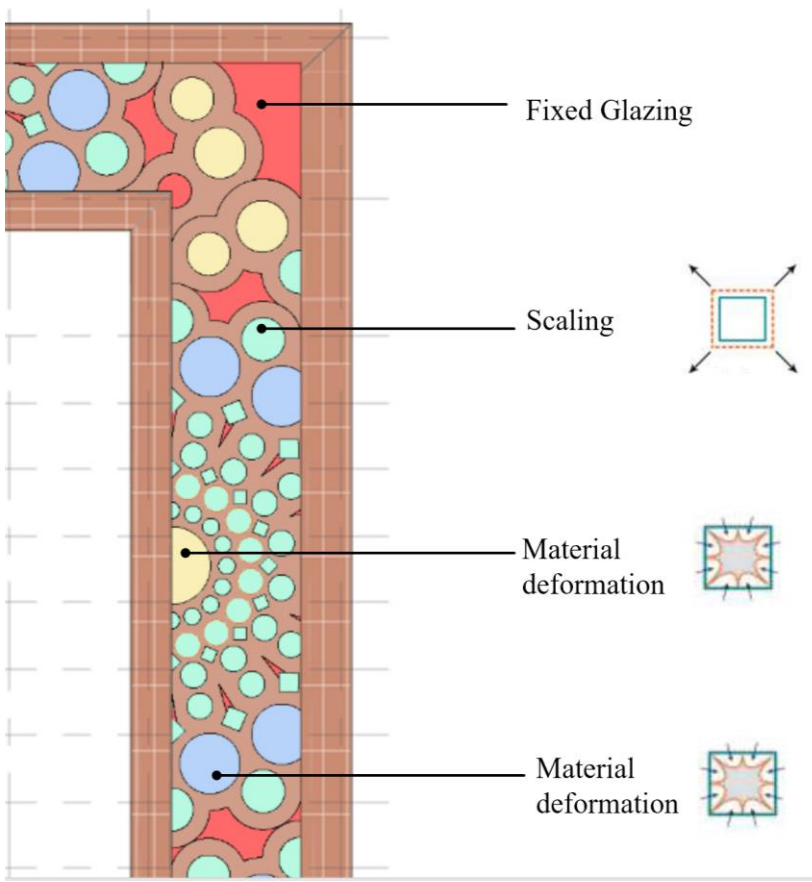
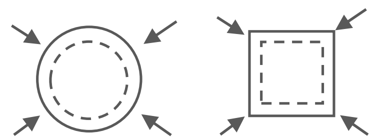
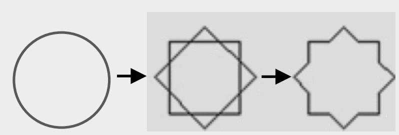
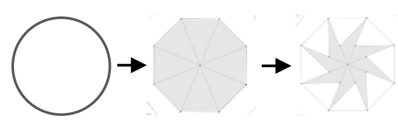
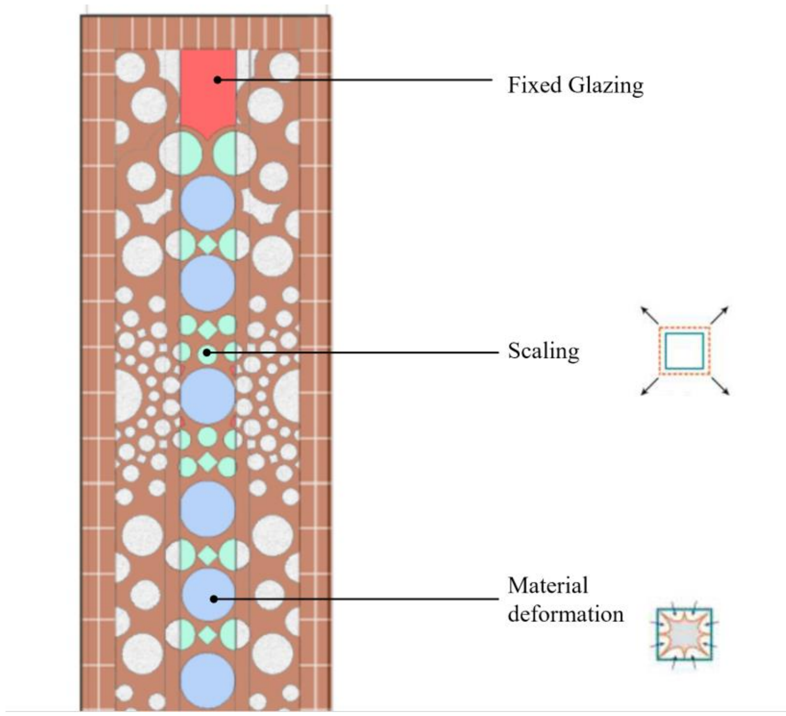
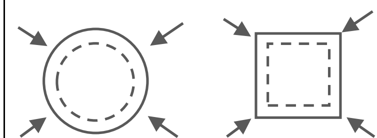
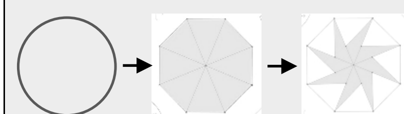
South and North Facade	Kinetic Movement classification	Actual Type of kinetic movement of the proposed geometrics
		Fixed Glazing with no movement
		Square and circle scaling 
		Circles transferred to Islamic ornament 
		Circles transferred to stars 

Table 22: Proposed kinetic movement/ East and West facade

East and West Facade	Kinetic Movement classification	Actual Type of kinetic movement of the proposed geometrics
		Fixed Glazing with no movement
		Square and circle scaling 
		Circles transferred to stars 

4.5.4 Stage four: Selecting the kinetic strategy

In this stage, kinetic strategies that are expected to affect the proposed kinetic system will be implemented to achieve the targeted performance in terms of energy, thermal and aesthetic values. The first strategy, which is energy performance-based design, will be achieved through WWR analysis and parametric design to result in different kinetic scenarios with an indication of their energy savings. The second strategy is thermal-based design where sun cast analysis will be investigated for the proposed kinetic scenarios to determine the most effective ratios in terms of sun exposure. The third strategy is aesthetic performance-based design where the proposed kinetic scenario will be adjusted based on the functionality of the building.

4.5.4.1 Energy performance-based design

1...1.1 Window to wall ratio analysis

Elzeyadi (2017) indicated that one of the parameters that affect automated movable screens typology is solid to void ratio. Moreover, Mahmoud & Elghazi (2016) have used a 20% of WWR in the base case and parametric design were used to adjust this ratio based on the performance of daylighting. On the other hand, in Dubai Green building evaluation system (Sa'fat), the requirements of glazing elements performance have increased in case of buildings with high percent of glazing elements due to its significant impact on energy performance, (Dubai Municipality 2007).

WWR is calculated by dividing the total glazing area on the total wall area. Several studies have investigated the impact of WWR in reference to daylighting, views and energy consumption to determine the optimal ratio for achieving optimal designs, (Yang et al. 2015) (Alibaba 2016). However, Feng et al. (2017) highlighted that the most efficient WWR in East and West façade ranges from 10 to 15%, in South façade from 10% to 22.5% and in North façade, it should be reduced whenever it is allowed by lighting and ventilation conditions.

In this research, the impact of WWR on electricity and cooling loads will be determined using IES VE software in order to select the optimal WWR of the kinetic movement through the proposed scenarios. Figure 51 describes how adjusting glazing elements ratio can be inserted in IES VE and Figure 52 shows the impact on the building total electricity and cooling loads as a result of editing the building WWR.

The researcher has calculated the existing WWR of South/North and East/West façade of the case study to be used as a base case in the analysis. Table 23 shows the existing WWR of each elevation in its base case and base case abstract, which is the new base design of the kinetic system that was developed in stage two, selecting the kinetic typology. It should be noted that South and North façade base case WWR equal 40% and East and West façade WWR equal 22%. On the other hand, in the base case abstract South and North façade base case WWR equal 30% and East and West façade WWR equal 15%.

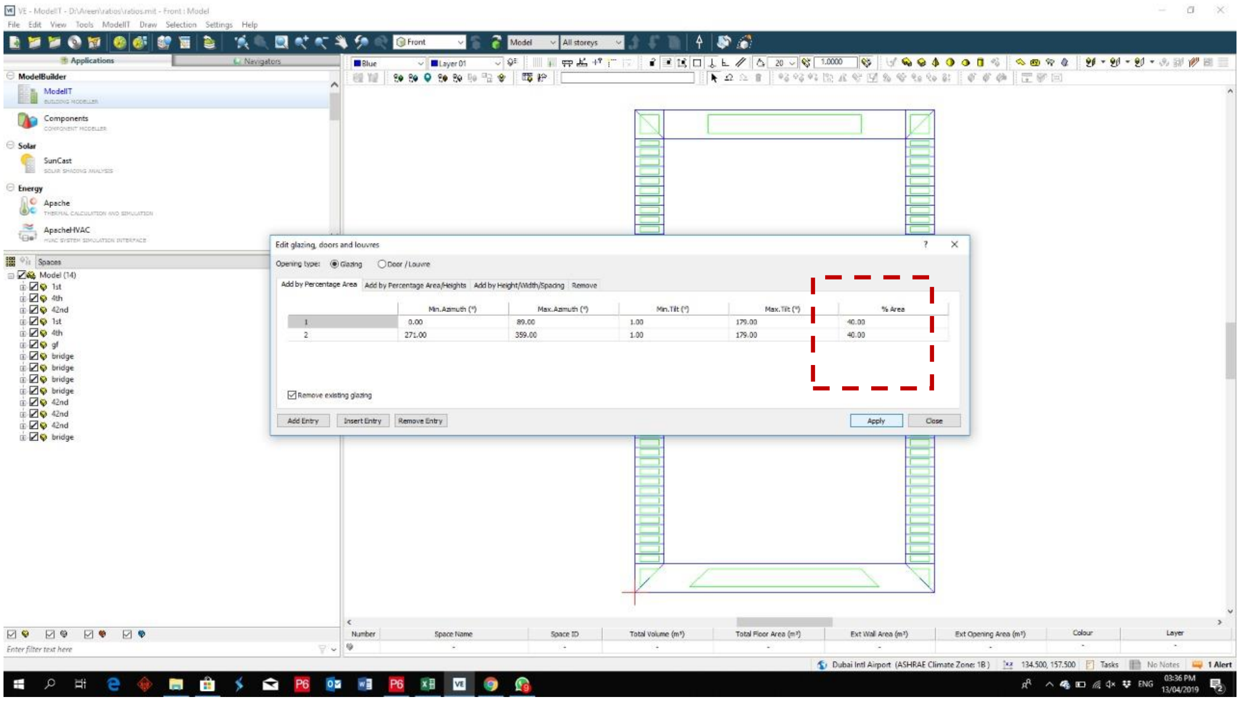


Figure 51: Selecting WWR of the South façade through IES VE

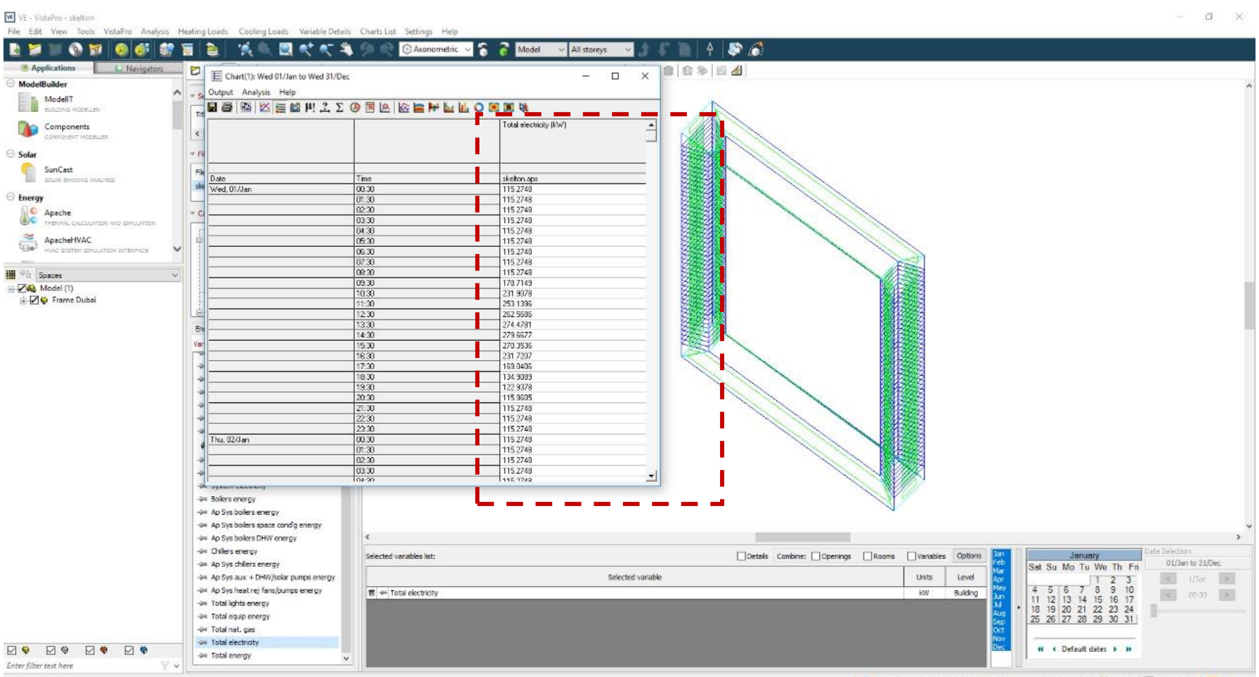


Figure 52: Total electricity results from adjust WWR of the building throughout the whole year-IES VE

Table 23: Base case and base case abstract WWR

Façade Location	Total façade area	Base case		Base case abstract	
		Total void area	WWR	Total void area	WWR
South/North	4493.94	1777.1	40.00%	1325.88	30.00%
East/West	2377.57	528.57	22.00%	346.48	15.00%

After calculating both base case and base case abstract WWR, a reduction of 5% in South/North WWR and 2% in East/West WWR was investigated through IES VE software to calculate the reduction in the building cooling loads. The researcher has selected three dates; 21st Dec, 21st June and 21st March and three timings; 8:30 AM, 12:30 PM and 17;30 PM to be used as an indication of energy savings when selecting the kinetic scenarios in stage four. Table 24 shows the base case cooling loads of the South, North, East and West façade.

Table 24: South, North, East and West façade base case cooling loads

South façade- Base case			
WWR	**Date**	**Time**	**Room cooling plant sens. load (kW)**
40%	21-Mar-19	8:30	104.30
		12:30	160.45
		17:30	104.84
	21-Jun-19	8:30	138.07
		12:30	171.65
		17:30	126.48
	21-Dec-19	8:30	91.75
		12:30	115.95
		17:30	92.66
North façade- Base case			
40%	21-Mar-19	8:30	87.17
		12:30	92.04
		17:30	89.92
	21-Jun-19	8:30	125.73
		12:30	124.39

		17:30	125.71
	21-Dec-19	8:30	82.43
		12:30	92.90
		17:30	85.65
East façade- Base case			
22%	21-Mar-19	8:30	89.81
		12:30	83.14
		17:30	83.26
	21-Jun-19	8:30	114.31
		12:30	107.32
		17:30	103.83
	21-Dec-19	8:30	112.67
		12:30	105.58
		17:30	103.79
West façade- Base case			
22%	21-Mar-19	8:30	81.83
		12:30	82.68
		17:30	87.30
	21-Jun-19	8:30	104.98
		12:30	106.67
		17:30	113.30
	21-Dec-19	8:30	81.18
		12:30	82.51
		17:30	81.45

On the other hand, Table 25 shows the proposed base case abstract cooling loads of the South facade and the reduction percentage of cooling loads when WWR is reduced by 5% starting from 25% to 10% in comparison with the base case cooling loads to identify the reduction percentages that would result from reducing the WWR in each façade.

The proposed WWR in Table 25 shows an average of 12% reduction in cooling loads in the base case abstract for the selected dates and timings and would reach up to 21% reduction when the WWR is 10%. It should be noted that these indicators are investigated in IES VE if the WWR is adjusted in the South façade only.

Table 25: The reduction of cooling loads as a result from reducing the WWR in the South facade

South façade				
WWR	**Date**	**Time**	**Room cooling plant sens. load (kW)**	**Cooling load reduction compared to base case**
30% Base case Abstract	21-Mar-19	8:30	94.20	10%
		12:30	136.22	15%
		17:30	99.09	5%
	21-Jun-19	8:30	119.76	13%
		12:30	136.10	21%
		17:30	121.19	4%
	21-Dec-19	8:30	89.19	3%
		12:30	106.94	8%
		17:30	90.45	2%
25%	21-Mar-19	8:30	95.99	8%
		12:30	124.08	23%
		17:30	97.27	7%
	21-Jun-19	8:30	116.72	15%
		12:30	131.31	24%
		17:30	116.14	8%
	21-Dec-19	8:30	87.78	4%
		12:30	103.06	11%
		17:30	88.95	4%
20%	21-Mar-19	8:30	95.99	8%
		12:30	124.08	23%
		17:30	94.64	10%
	21-Jun-19	8:30	116.72	15%
		12:30	131.31	24%
		17:30	114.87	9%
	21-Dec-19	8:30	87.78	4%
		12:30	103.06	11%
		17:30	85.47	8%
15%	21-Mar-19	8:30	90.30	13%
		12:30	106.23	34%
		17:30	91.71	13%
	21-Jun-19	8:30	112.22	19%
		12:30	119.11	31%
		17:30	113.89	10%
	21-Dec-19	8:30	85.69	7%

		12:30	94.05	19%
		17:30	84.15	9%
10%	21-Mar-19	8:30	87.44	16%
		12:30	97.90	39%
		17:30	89.48	15%
	21-Jun-19	8:30	109.19	21%
		12:30	114.14	34%
		17:30	111.62	12%
	21-Dec-19	8:30	80.61	12%
		12:30	90.08	22%
		17:30	79.50	14%

Moreover, Table 26 shows the proposed base case abstract cooling loads of the North façade along with the same proposed WWR of the South façade, which ranges from 25% to 10% to be compared with the North façade base case cooling loads. It should be noted that Table 26 shows an average of 1% reduction in cooling loads in the base case abstract for the selected dates and timings and would reach up to 11% reduction when the WWR is 10%.

Table 26 :The reduction of cooling loads as a result from reducing the WWR in the North facade

North façade				
WWR	**Date**	**Time**	**Room cooling plant sens. load (kW)**	**Cooling load reduction compared to base case**
30% Base case Abstract	21-Mar-19	8:30	86.91	0%
		12:30	91.51	1%
		17:30	89.53	0%
	21-Jun-19	8:30	125.03	1%
		12:30	123.32	1%
		17:30	124.30	1%
	21-Dec-19	8:30	82.32	0%
		12:30	92.42	1%
		17:30	85.49	0%
25%	21-Mar-19	8:30	84.64	3%
		12:30	87.65	5%
		17:30	86.87	3%
	21-Jun-19	8:30	115.61	8%
		12:30	115.19	7%
		17:30	116.02	8%
	21-Dec-19	8:30	78.68	5%

		12:30	88.26	5%
		17:30	81.18	5%
20%	21-Mar-19	8:30	83.87	4%
		12:30	86.12	6%
		17:30	85.82	5%
	21-Jun-19	8:30	113.34	10%
		12:30	112.57	10%
		17:30	112.79	10%
	21-Dec-19	8:30	81.03	2%
		12:30	85.35	8%
		17:30	83.30	3%
15%	21-Mar-19	8:30	80.99	7%
		12:30	83.96	9%
		17:30	84.79	6%
	21-Jun-19	8:30	110.10	12%
		12:30	107.93	13%
		17:30	110.94	12%
	21-Dec-19	8:30	79.29	4%
		12:30	83.12	11%
		17:30	80.68	6%
10%	21-Mar-19	8:30	80.07	8%
		12:30	81.20	12%
		17:30	83.77	7%
	21-Jun-19	8:30	106.44	15%
		12:30	105.83	15%
		17:30	105.13	16%
	21-Dec-19	8:30	78.34	5%
		12:30	80.22	14%
		17:30	80.31	6%

In addition, Table 27 shows the proposed base case abstract cooling loads of the East façade and the reduction percentage of cooling loads when WWR is reduced by 2% starting from 15% to 6% in comparison with the East facade base case cooling loads to investigate the impact of reducing WWR on the East façade. The average reduction of cooling loads ranges from 2% when WWR is 15% up to 4% when WWR is 10%. This average is calculated for each ratio selected dates and timings cooling loads.

Table 27: The reduction of cooling loads as a result from reducing the WWR in the East facade

East façade				
WWR	**Date**	**Time**	**Room cooling plant sens. load (kW)**	**Cooling load reduction compared to base case**
15% Base case Abstract	21-Mar-19	8:30	85.54	5%
		12:30	81.99	1%
		17:30	82.56	1%
	21-Jun-19	8:30	109.99	4%
		12:30	103.41	4%
		17:30	103.50	0%
	21-Dec-19	8:30	80.92	0%
		12:30	81.61	1%
		17:30	80.87	0%
12%	21-Mar-19	8:30	83.69	7%
		12:30	81.57	2%
		17:30	82.28	1%
	21-Jun-19	8:30	108.12	5%
		12:30	102.72	4%
		17:30	102.97	1%
	21-Dec-19	8:30	80.76	1%
		12:30	81.23	2%
		17:30	80.71	1%
10%	21-Mar-19	8:30	83.07	8%
		12:30	81.22	2%
		17:30	82.09	1%
	21-Jun-19	8:30	106.99	6%
		12:30	102.27	5%
		17:30	103.14	1%
	21-Dec-19	8:30	80.66	1%
		12:30	80.98	2%
		17:30	80.60	1%
8%	21-Mar-19	8:30	82.38	8%
		12:30	80.87	3%
		17:30	81.83	2%
	21-Jun-19	8:30	105.52	8%
		12:30	102.35	5%
		17:30	101.54	2%
	21-Dec-19	8:30	80.542	1%

		12:30	80.72	2%
		17:30	80.51	1%
6%	21-Mar-19	8:30	81.77	9%
		12:30	80.58	3%
		17:30	81.67	2%
	21-Jun-19	8:30	103.13	10%
		12:30	100.63	6%
		17:30	101.35	2%
	21-Dec-19	8:30	80.47	1%
		12:30	80.49	2%
		17:30	80.41	1%

Furthermore, Table 28 shows the proposed base case abstract cooling loads of the West façade and the reduction percentage of cooling loads when WWR is reduced by 2% starting from 15% to 6% in comparison with the West facade base case cooling loads. The average reduction of cooling loads ranges from 2% when WWR is 15% up to 4% when WWR is 10%, which is similar to the East façade reduction percentages.

Table 28: The reduction of cooling loads as a result from reducing the WWR in the West facade

West façade				
WWR	**Date**	**Time**	**Room cooling plant sens. load (kW)**	**Cooling load reduction compared to base case**
15% Base case Abstract	21-Mar-19	8:30	81.14	1%
		12:30	81.68	1%
		17:30	85.39	2%
	21-Jun-19	8:30	102.69	2%
		12:30	103.17	3%
		17:30	109.40	3%
	21-Dec-19	8:30	80.88	0%
		12:30	81.63	1%
		17:30	81.01	1%
12%	21-Mar-19	8:30	80.89	1%
		12:30	81.26	2%
		17:30	84.68	3%
	21-Jun-19	8:30	102.33	3%
		12:30	102.52	4%
		17:30	106.62	6%
	21-Dec-19	8:30	80.69	1%

		12:30	81.23	2%
		17:30	80.86	1%
10%	21-Mar-19	8:30	80.72	1%
		12:30	80.98	2%
		17:30	84.10	4%
	21-Jun-19	8:30	101.63	3%
		12:30	101.98	4%
		17:30	104.97	7%
	21-Dec-19	8:30	80.61	1%
		12:30	80.99	2%
		17:30	80.74	1%
8%	21-Mar-19	8:30	80.55	2%
		12:30	80.69	2%
		17:30	83.52	4%
	21-Jun-19	8:30	100.94	4%
		12:30	101.44	5%
		17:30	103.31	9%
	21-Dec-19	8:30	80.54	1%
		12:30	80.75	2%
		17:30	80.61	1%
6%	21-Mar-19	8:30	80.37	2%
		12:30	80.43	3%
		17:30	82.94	5%
	21-Jun-19	8:30	101.56	3%
		12:30	100.58	6%
		17:30	103.42	9%
	21-Dec-19	8:30	80.45	1%
		12:30	80.50	2%
		17:30	80.48	1%

Following the analysis highlighted in this section, there is a significant impact of reducing the cooling loads as a result from reducing the WWR of each façade. However, to design the kinetic movement based on these figures, a parametric model will be created in the following section to identify the behaviour of the façade based on these ratios. Moreover, these figures will be used in stage four, selecting the kinetic scenarios, to be an indicator of the reduction in both cooling loads and electricity consumption of each scenario to achieve the targeted performance levels along with the other strategies that would assess the researcher in proposing an optimal kinetic system of the selected case study.

1...1.2 Parametric Model - Grasshopper

The proposed design of the building façade was created by developing four group of movement mechanisms, which was proposed in stage three, selecting the kinetic mechanism, in order to be used as the base of the parametric model to result in transforming each façade in the building into a kinetic façade with reference to different WWR that was listed in the previous section of this strategy.

In this stage, a parametric model was developed to identify the movement mechanism of each geometry in response to the proposed WWR of each elevation using Grasshopper environment that runs within Rhino 3D application. Grasshopper provides designers an intuitive way to explore design since it is a visual programming language.

The parametric model evaluates in moment the ratio between void area and the total area (WWR) which allows the researcher to capture the exact façade configuration in various movement scenarios. To control the different types of movement mechanisms, all were connected to a factor that ranges from 0 to 1; where 0 presents the least value of void area and 1 presents the highest value of void area that both could be reached from the movement of the solid plates in each mechanism. Figure 53 shows the complete script of the parametric model in grasshopper.

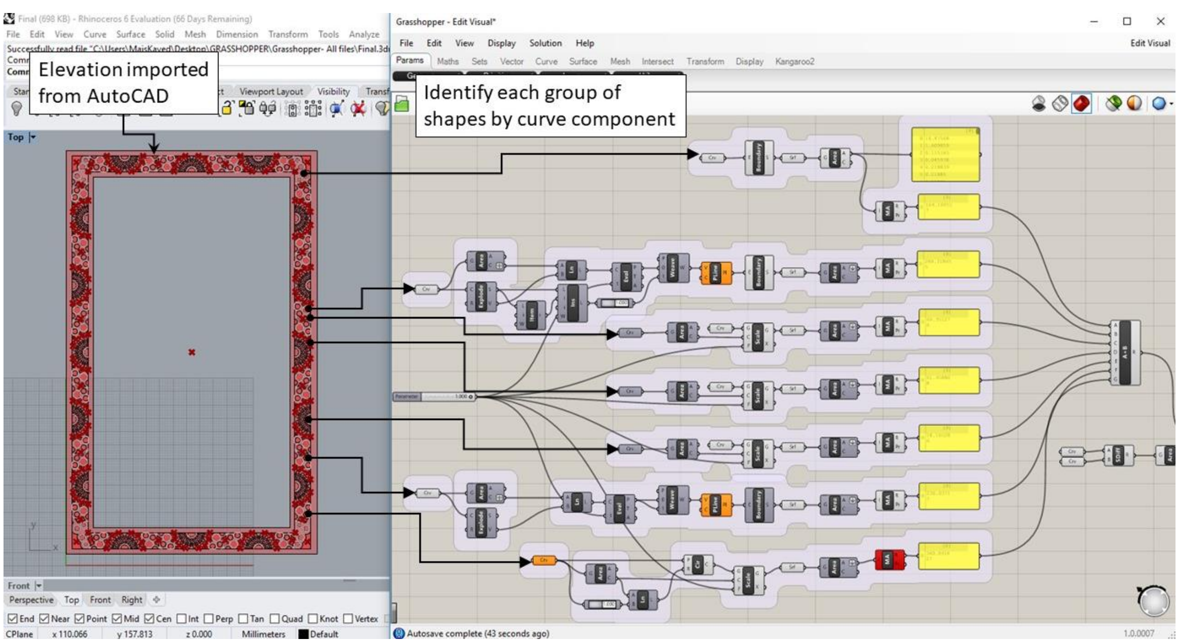


Figure 53: The complete script of the parametric model in Grasshopper.

First of all, the elevation was imported from AutoCAD in its abstracted conditions that was developed in stage two, selecting the kinetic typology, then each group of geometries that share the same movement mechanism was identified in grasshopper using curve component (set multiple curves -> select the shape from rhino window).

The script of the developed parametric model consists of three groups of components; (i) void area component, (ii) facade total area component, (iii) components to evaluate and measure the ratio between the façade and the void total area (WWR) as shown in Figure 54 below.

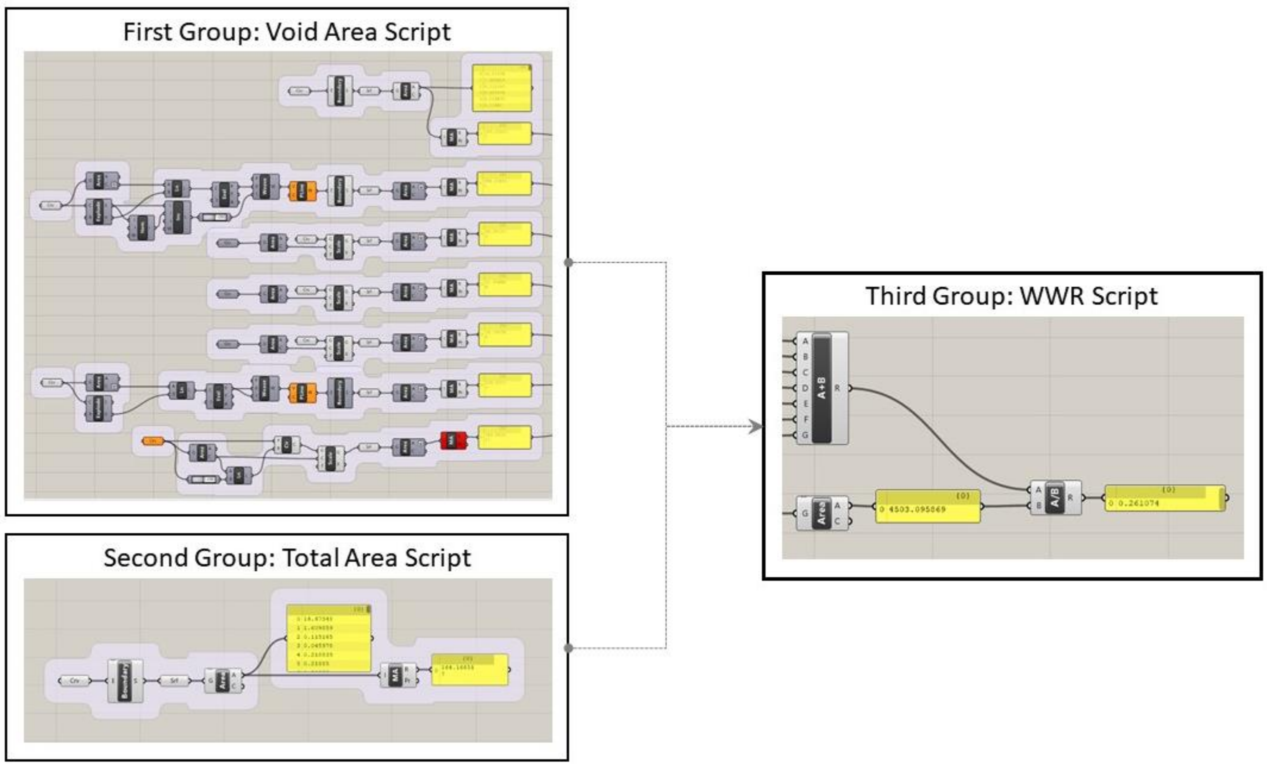


Figure 54: The proposed components of the parametric model

I. **First group: Void area script**.

The first group of the parametric model is the void area script that is described in details in

Figure 55, and it includes the area of four types of openings that was identified in Table 21 and Table 22, stage two, selecting the kinetic mechanism.

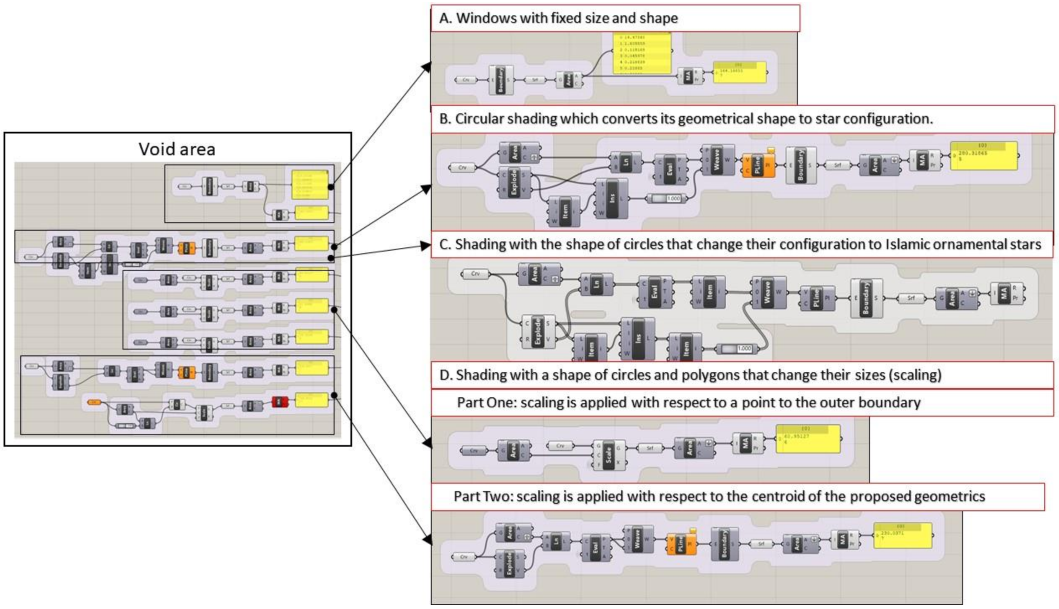


Figure 55: Void area parametric model script

The technical coding of the void area group was divided to four sub-groups based on the type of openings and coded based on each geometric kinetic behaviour as follows:

a. Windows with fixed shape and size.

Windows fixed shapes are defined as curve, then the boundary of each shape is defined to enable the parametric model to calculate the area of each surface and combine them together to result in a total area of fixed glazing elements as described in Figure 56 and
Figure 57.

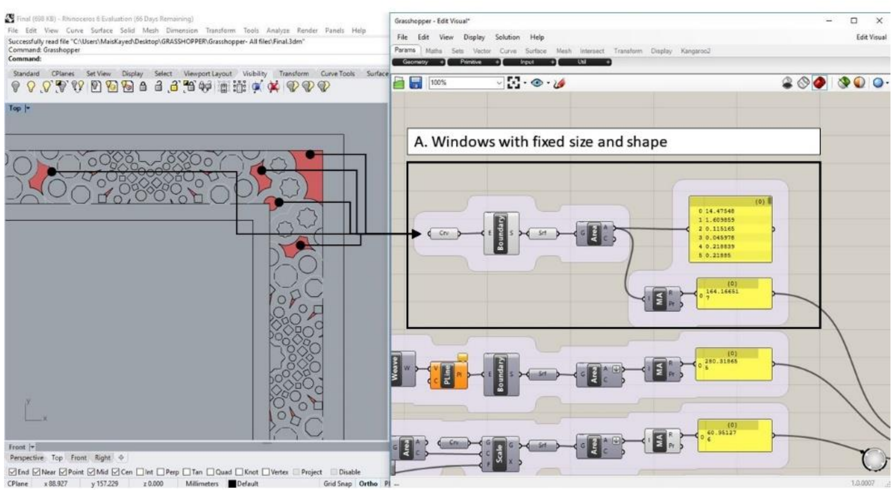


Figure 56: Windows with fixed shape and size parametric model script and selection

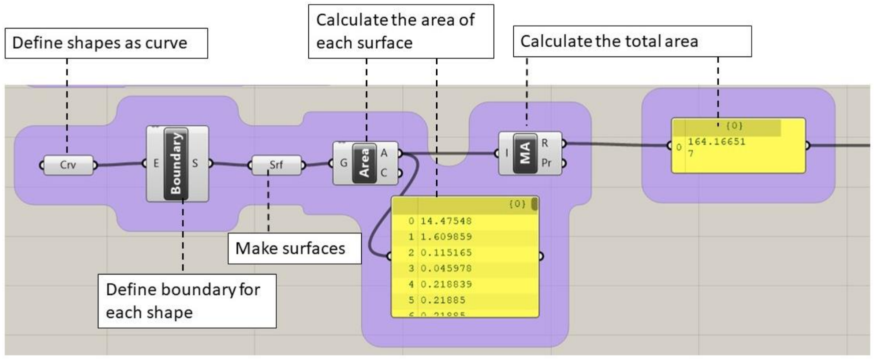


Figure 57: Windows with fixed shape and size parametric model technical details

b. Circular shading which converts its geometrical shape to star configuration.

The circular shading that converts to a star configuration goes through different stages starting from an octagonal shape that is linked with different factors and segments, which represents the behaviour of the shading object to create a surface that close and open as described in Figure 59 below. On the other hand, the selection and the description of the technical script to develop this kinetic behaviour are shown in details in Table 29 and Figure 58.

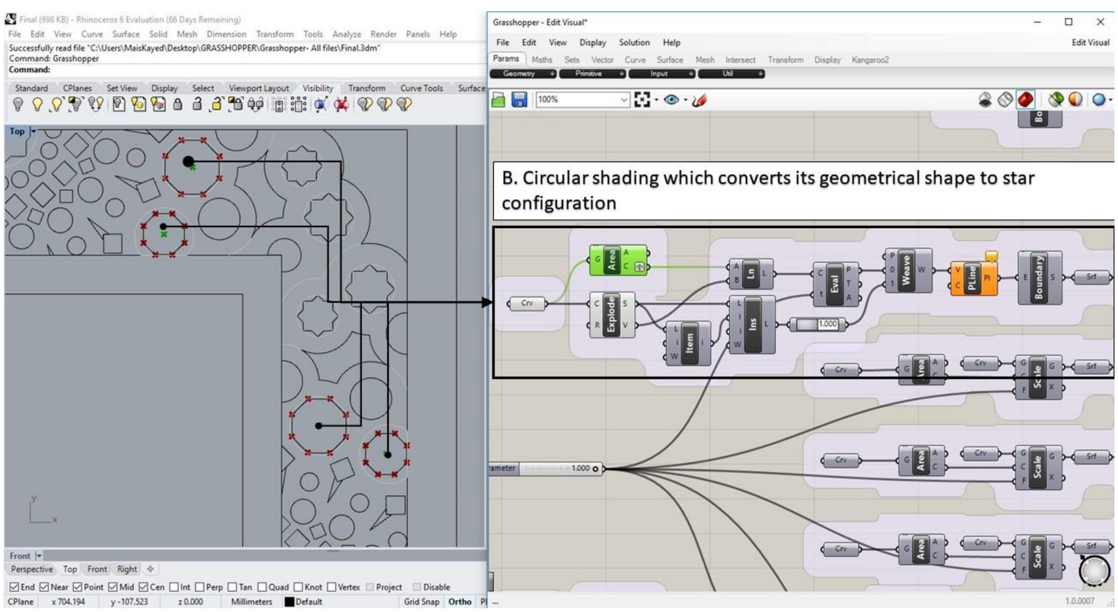
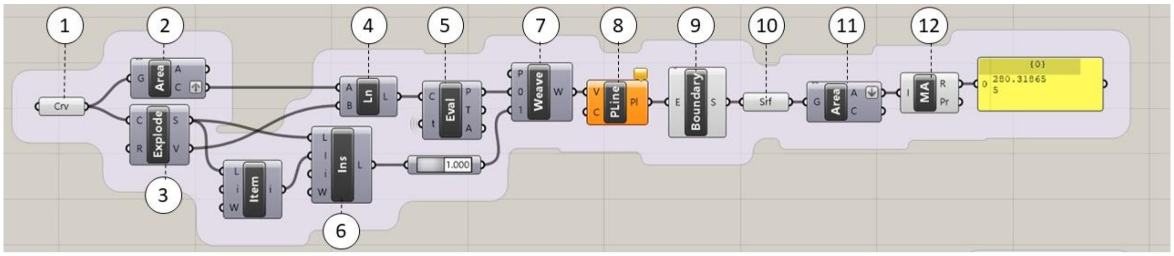


Figure 58: Circular shading to star configuration parametric model script and selection

Table 29: Circular shading to star configuration parametric model script



Legend:

1. Define shapes as curve.
2. Define the centroid for each shape.
3. Segment the circle into 8 segments.
4. Create lines between each segment point and the centroid.
5. Link the length of line with the factor.
6. Create list of segments points start and end with the same point.
7. Combine two lists of point with specific organization pattern.
8. Create polyline from list of points that was created in (7).
9. Define the polyline as boundary.
10. Create surfaces
11. Calculate area for each shape
12. Calculate the total area.

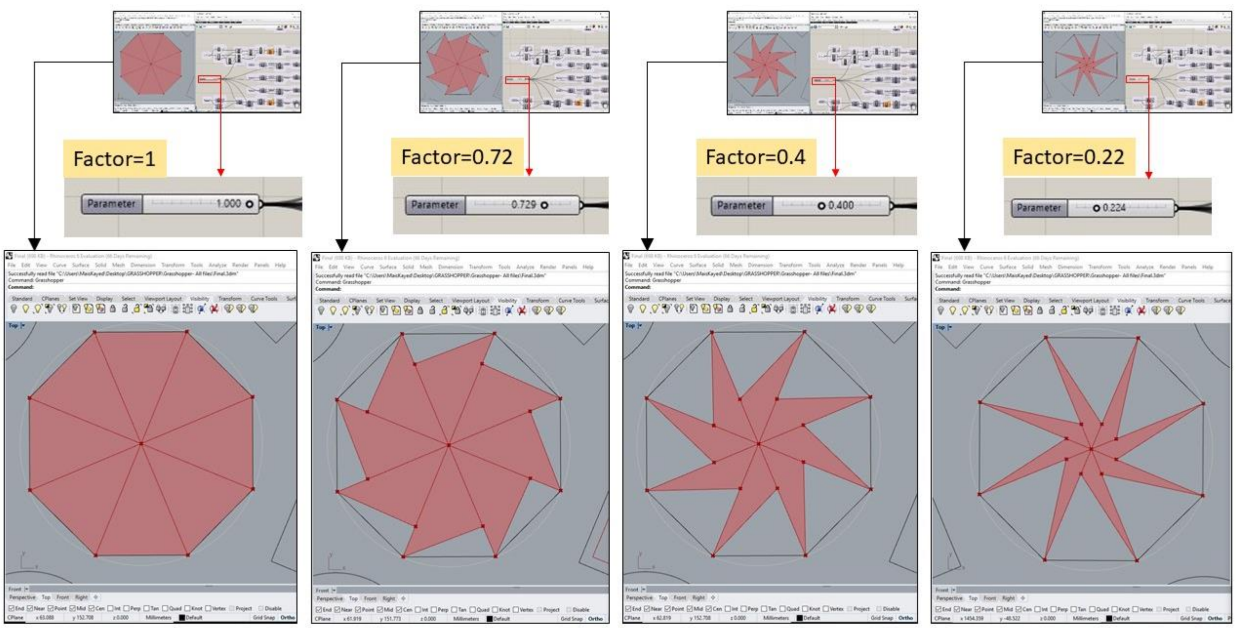


Figure 59: Circular shading to star configuration movement mechanism

c. **Shading with the shape of circles that change their configuration to Islamic ornamental stars with respect to a point in the boundary.**

The circular shading that converts to an Islamic ornamental star goes through different stages starting from defining the shape and its centroid then segment the shape to eight points that is linked with different factors which defines the behaviour of the shading object to create a surface that response to the proposed WWR as described in Figure 60 below.

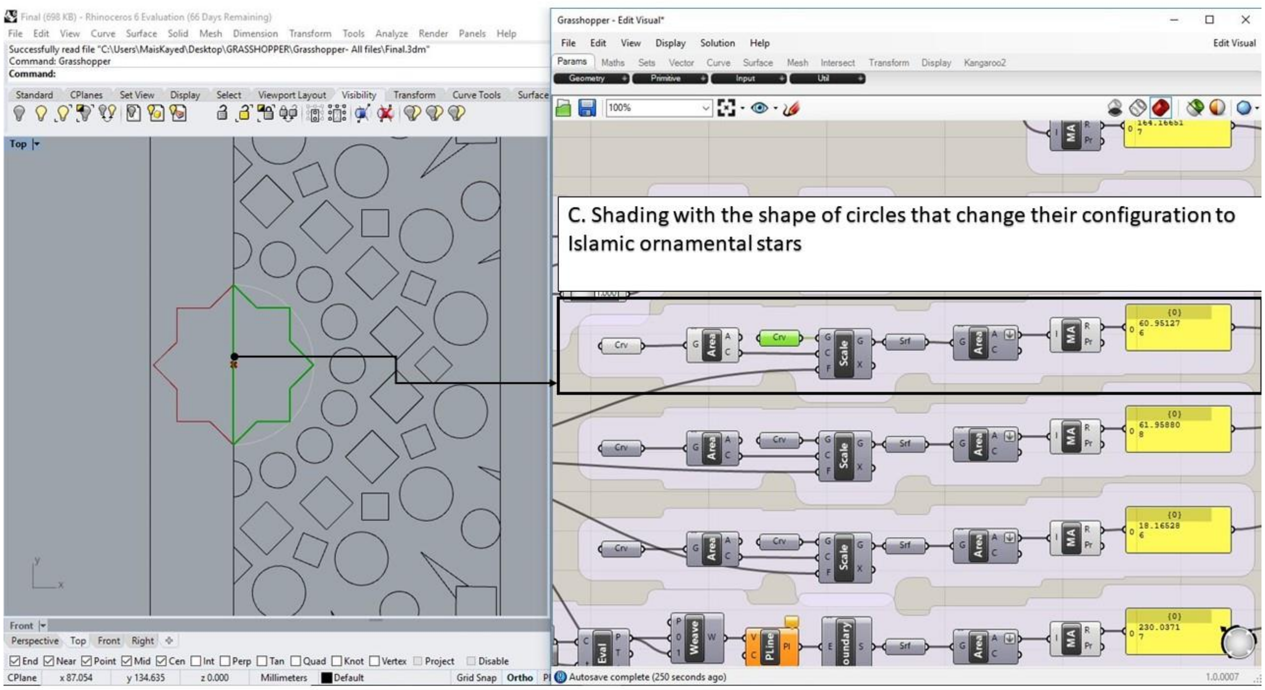
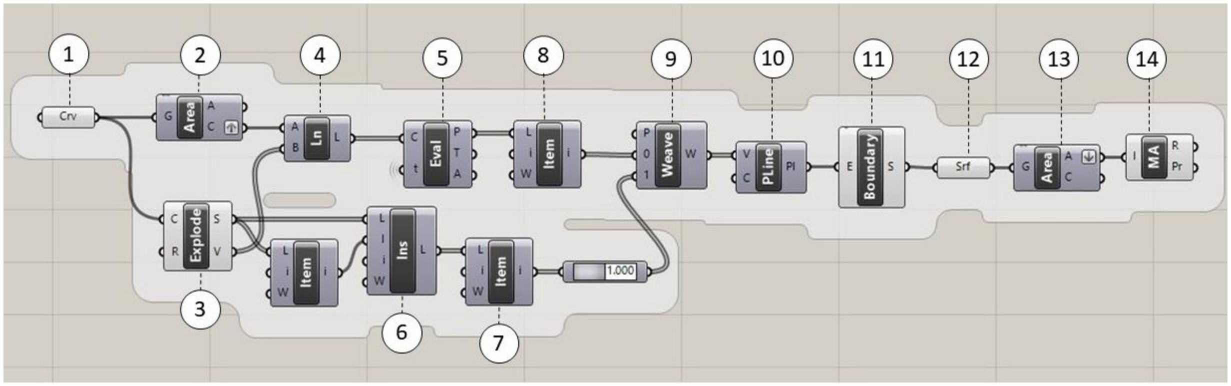


Figure 60: Circular shading to an Islamic ornamental star configuration parametric model and selection

Table 30: Circular shading to an Islamic ornamental star configuration parametric



Legend:

1. Define shapes (ornamental star) as curve. 2. Define the centroid for each shape. 3. Segment the circle into 8 segments. 4. Create lines between each segment point and the centroid. 5. Link the length of line with the factor. 6. Create list of segments points start and end with the same point. 7. Create a new list of points that defines half of the ornamental star geometry	8. Create list of the start points of lines created at step 4. 9. Organize the sequence of points to create the polyline 10. Create polyline from list of points that was created in (9). 11. Define the polyline as boundary. 12. Create surfaces 13. Calculate area for each shape 14. Calculate the total area.

d. Shading with a shape of circles and polygons that change their sizes (scaling)

Scaling circles and polygons parametric model is divided to two parts as those shapes are identified in the façade as a whole shape or half of its area. Therefore, two types of scripts were developed in Grasshopper to accommodate their kinetic behaviour.

In the first part, scaling is applied with respect to a point in the outer boundary of the façade frame. Figure 61 describes the reference point of the shading with the shape of half a circle and half a square in the outer boundary. Moreover, the parametric script of this part is identified in Figure 62.

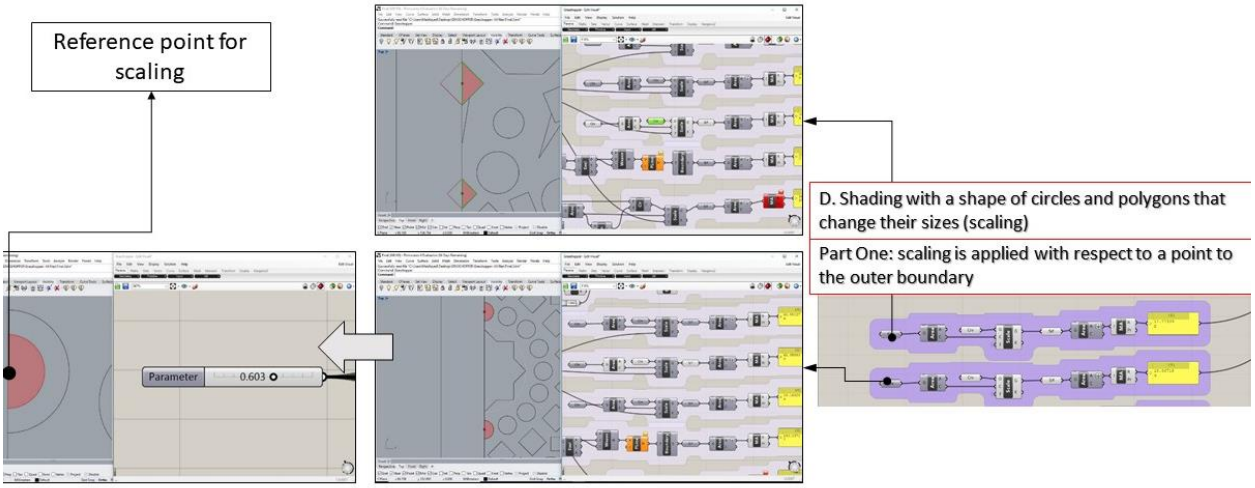


Figure 61: Shading with a shape of circles and polygons to indicate the reference point of scaling

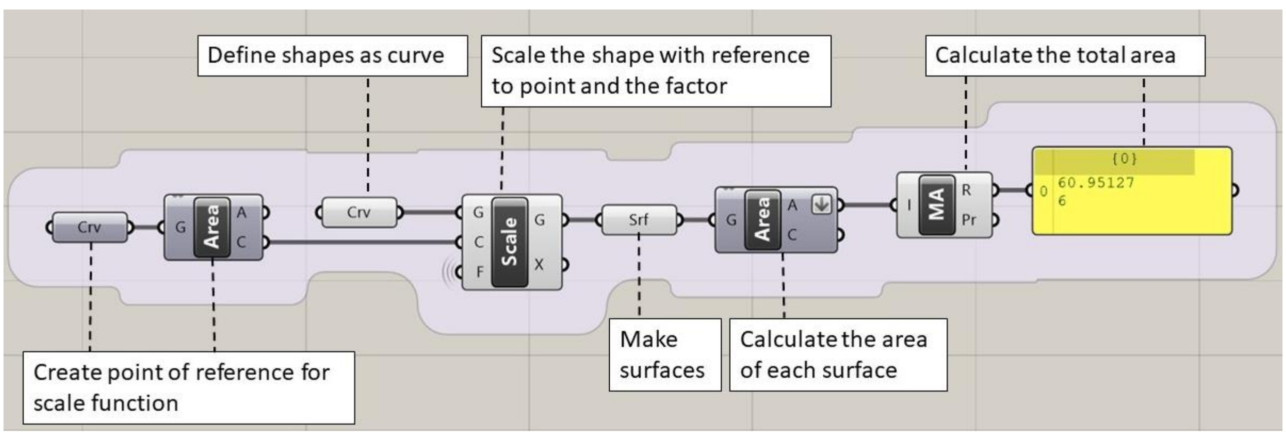


Figure 62: Shading with a shape of circles and polygons’ parametric script

On the other hand, in the second part, scaling is applied with respect to the centroid of the proposed geometrics. In this, however, a parametric script is required for each shape; the circle and the polygon as each shape centroid need to be coded separately.

Figure 63 describes the proposed geometries scaling in respect to its own centroid. Moreover, Table 31 identifies the first parametric script in the case of a polygon and Table 32 indicates the second parametric script in the case of a circle.

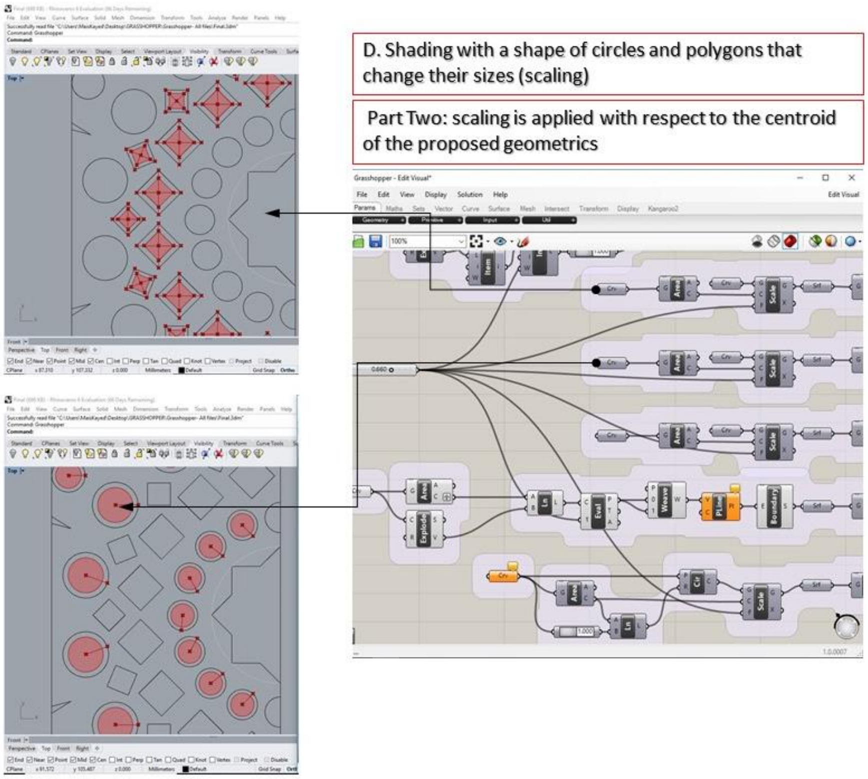


Figure 63: Shading with a shape of circles and polygons based on its own centroid

Table 31: Polygon scaling parametric script

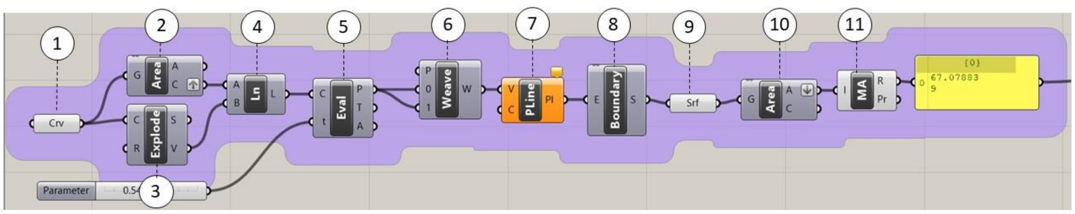
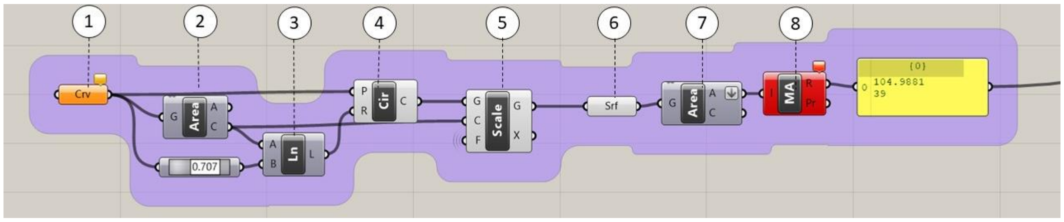
The case of a polygon	
	
Legend:	
15. Define shapes as curve. 16. Define the centroid for each shape. 17. Segment each shape. 18. Create lines between the segment point and the centroid. 19. Link the length of line with the factor. 20. Weave pattern of input indices	21. Create polyline from list of points that was created in (7). 22. Define the polyline as boundary. 23. Create surfaces 24. Calculate area for each shape 25. Calculate the total area.

Table 32: Circle scaling parametric script

The case of a circle	
	
Legend:	
1. Define shapes as curve. 2. Define the centroid for each shape. 3. Create lines between point on the curve and the centroid. 4. Define curve a circle.	5. Link each circle radius to the factor. 6. Create surfaces 7. Calculate area for each shape 8. Calculate the total area.

II. Second group: Total area script

The total area of the façade was connected to each shape area. In case of South and North façades, the total area was identified as the area resulted from the difference between the area of the outer boundary and the area of the inner boundary as described in Figure 64 that shows the total area parametric script of both South and North façade.

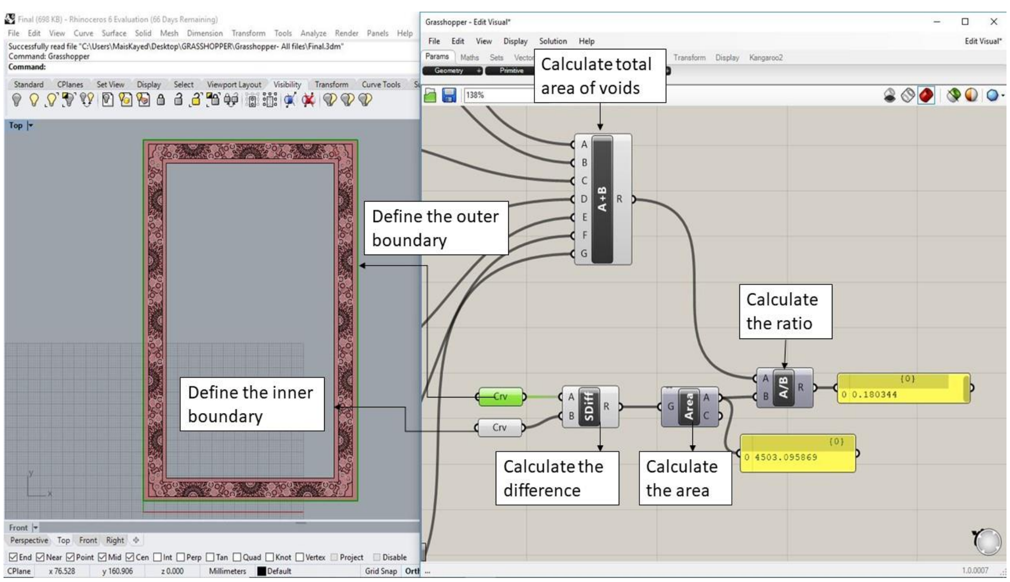


Figure 64: The total area parametric script of both South and North façade.

In case of East and West facades, the total area equals the area of the outer boundary, which was connected to each shape area to determine its kinetic movement. Figure 65 below describes the parametric script of East and West façade total area.

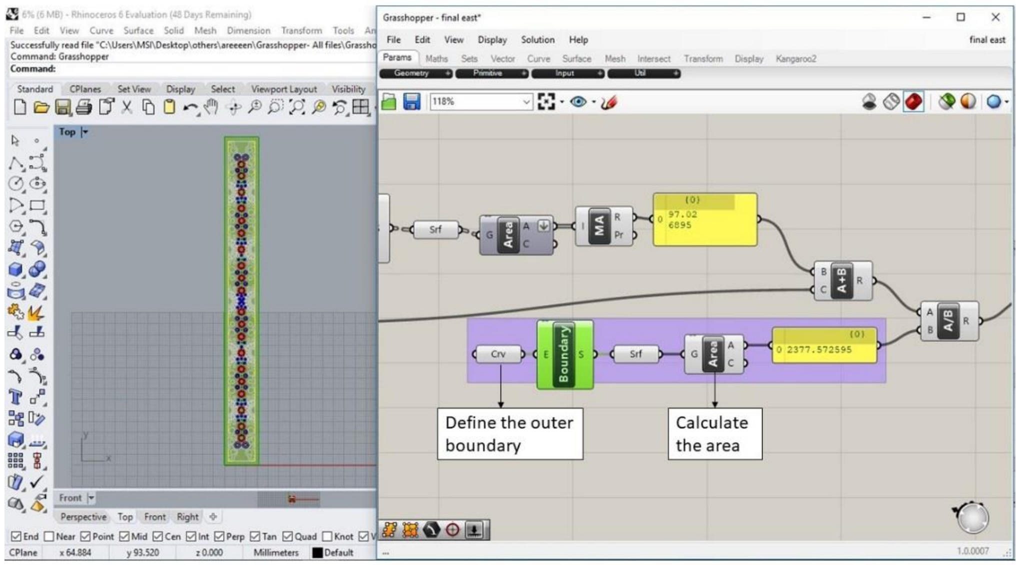


Figure 65: East and West façade total area parametric script

III. Third group: WWR script

The third group of the parametric model is the group that can be adjusted to achieve different kinetic scenarios of each façade with different WWR as proposed by the researcher. This script is connected to the void area parametric model that control the void area in each shape and the total area parametric model which would be required for calculating the proposed WWR. Refer to Figure 66.

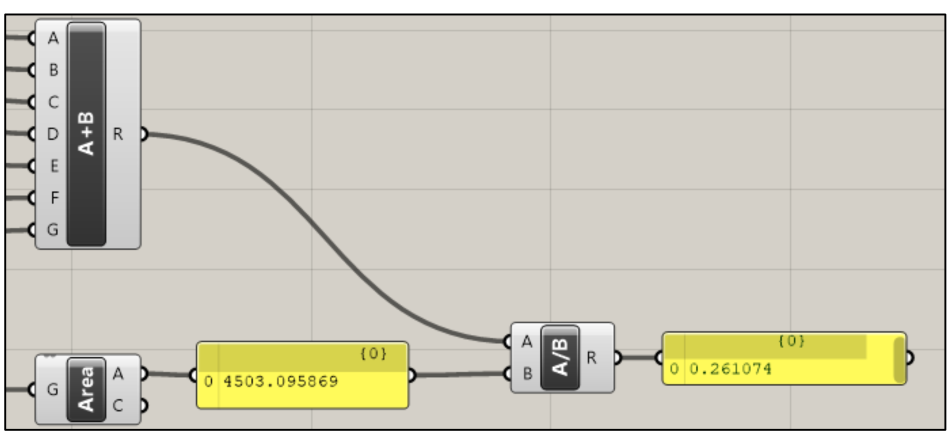
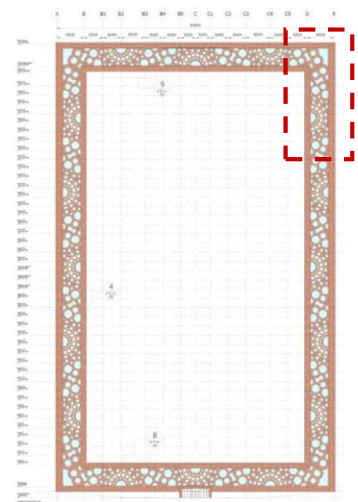
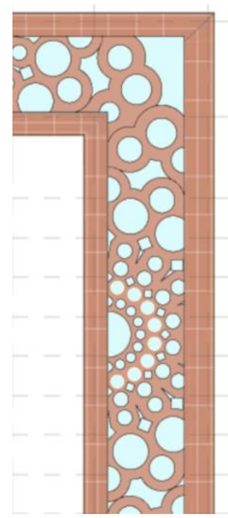
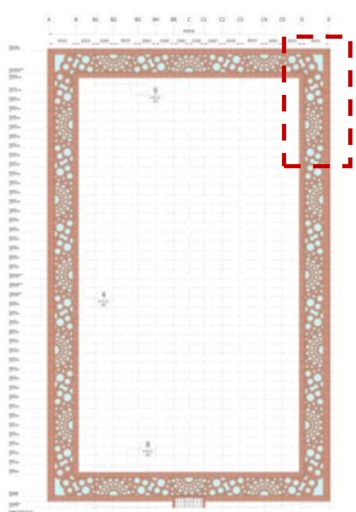
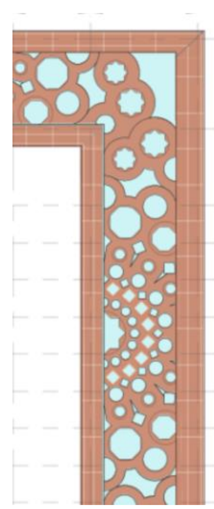


Figure 66: WWR parametric script

Different forms of facades were generated to describe the kinetic behaviour of each geometry as a result from developing the parametric model that identifies the movement mechanism of each geometry in response to the proposed WWR of each façade. Table 33 and Table 34 illustrate the form of each façade with respect to its WWR as generated from Grasshopper parametric model.

Table 33: South and North façade kinetic movement for different WWR as generated from Grasshopper

WWR	South and North Façade form	Repetitive unit
Base case (Abstract): 30%		
25%		

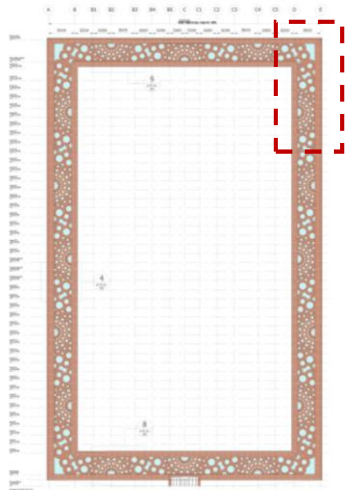
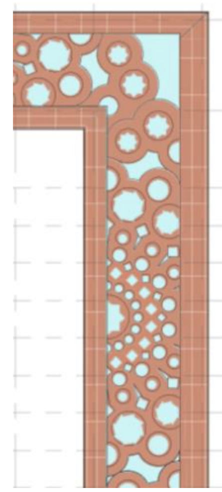
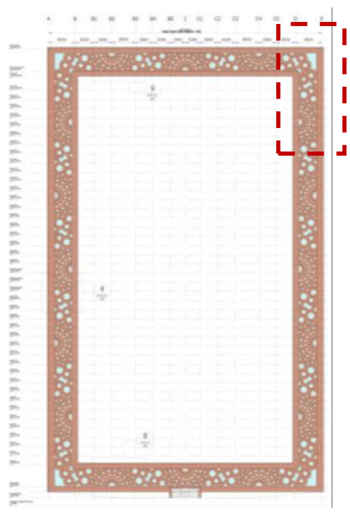
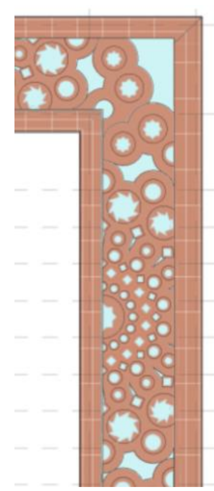
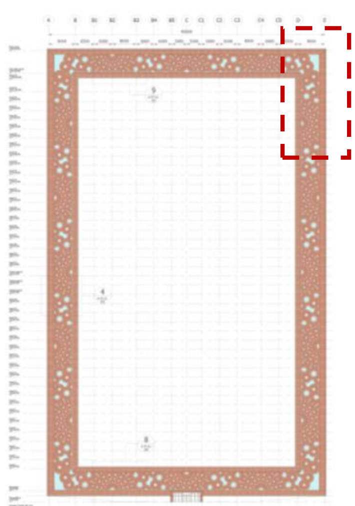
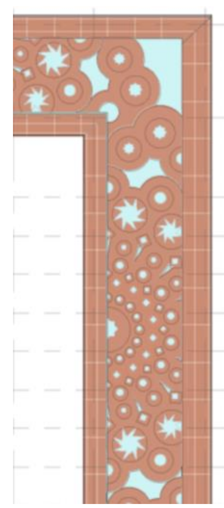
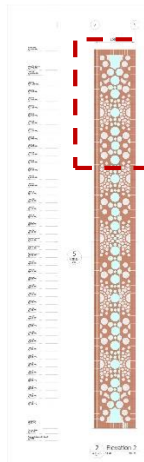
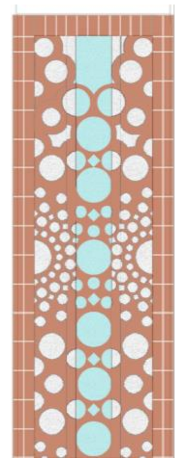
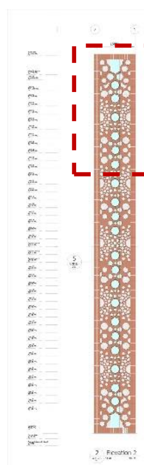
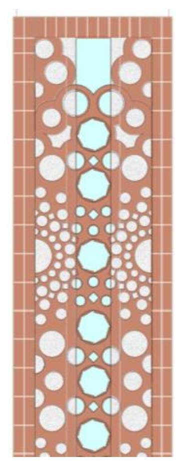
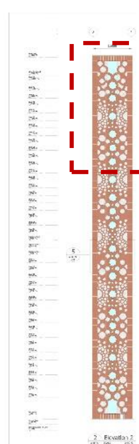
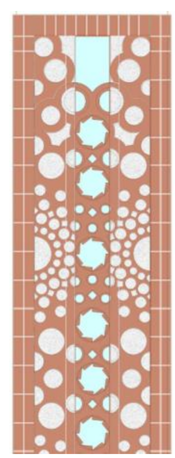
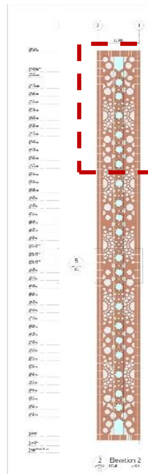
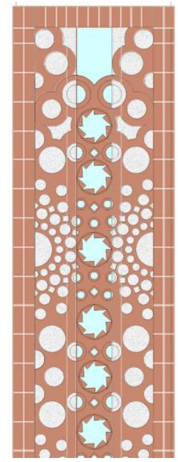
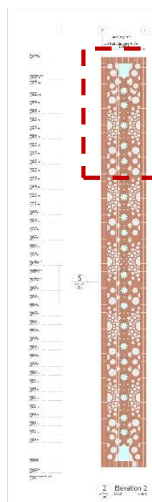
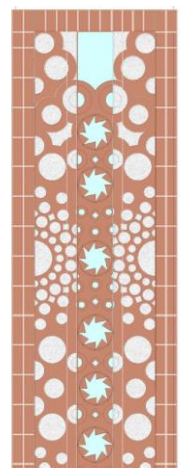
20%		
15%		
10%		

Table 34: East and West façade kinetic movement for different WWR as generated from Grasshopper

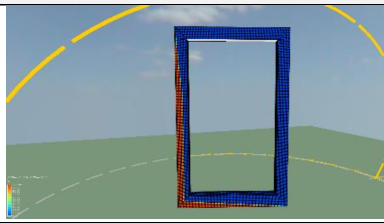
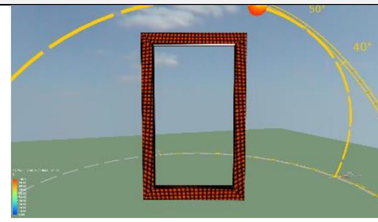
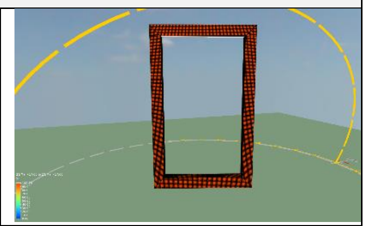
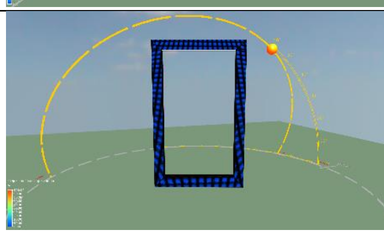
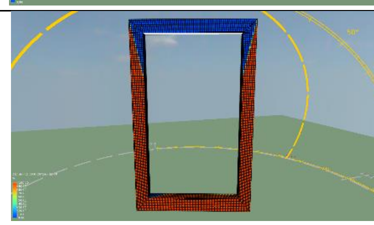
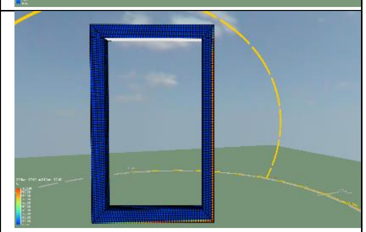
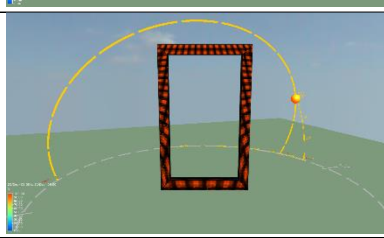
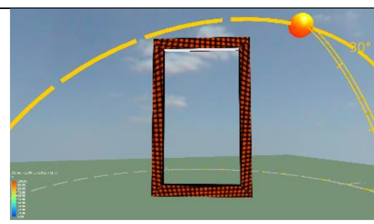
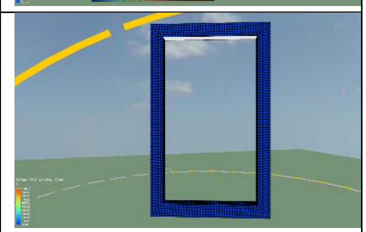
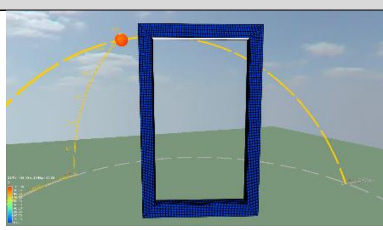
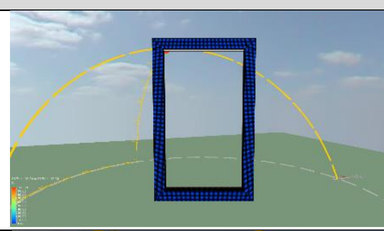
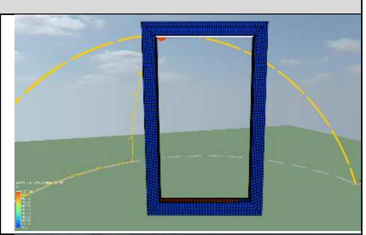
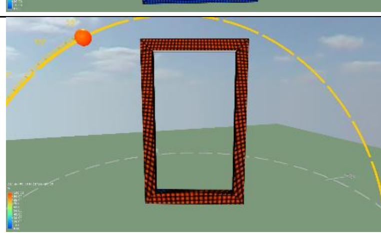
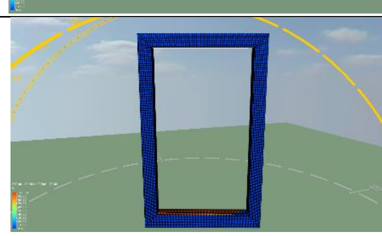
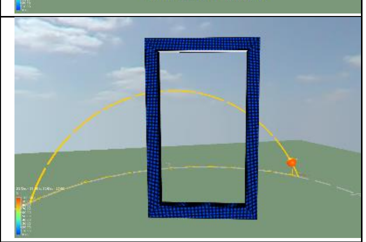
WWR	East and West Façade form	Repetitive unit
15%		
12%		
10%		

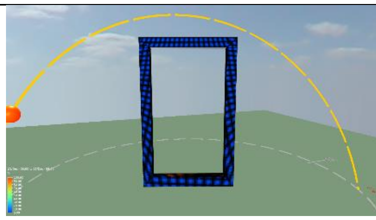
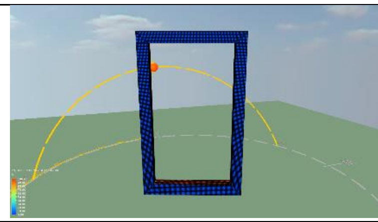
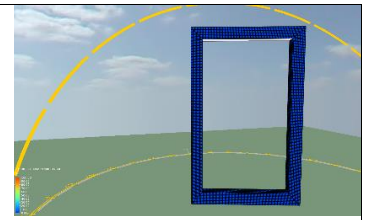
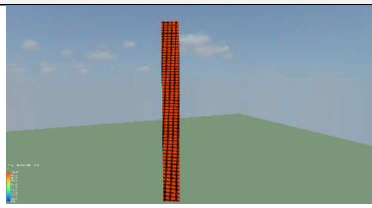
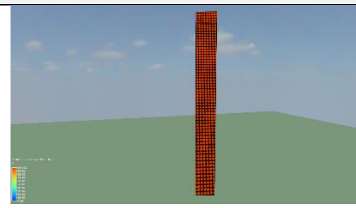
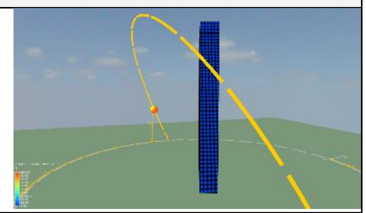
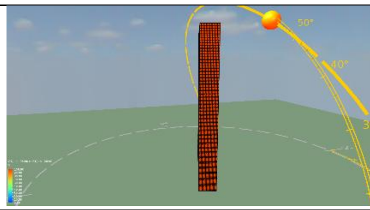
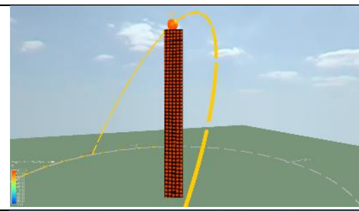
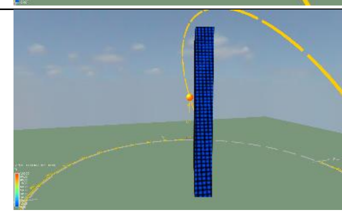
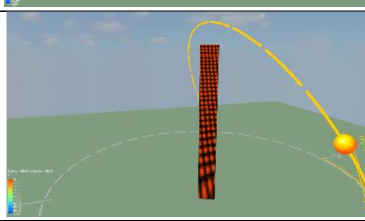
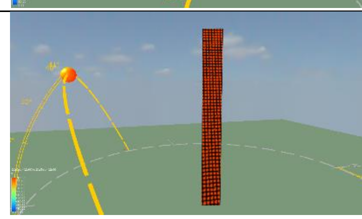
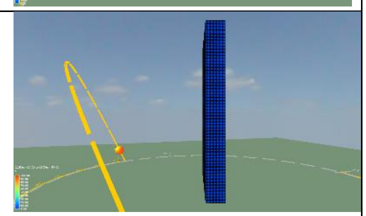
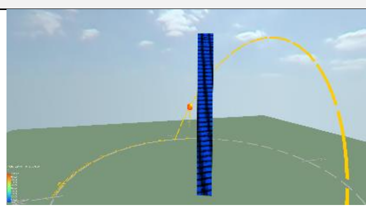
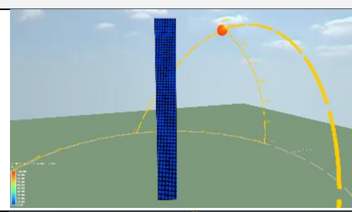
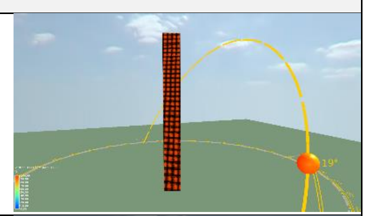
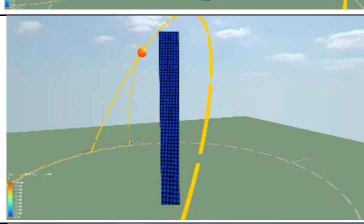
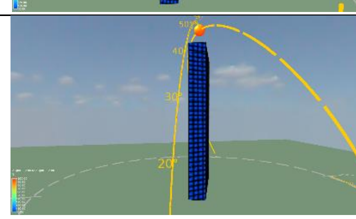
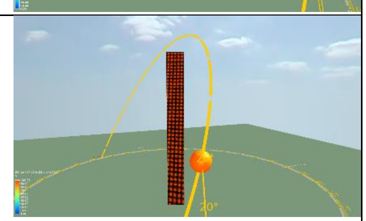
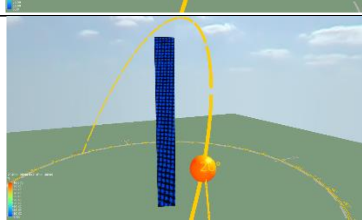
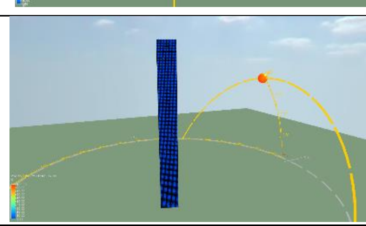
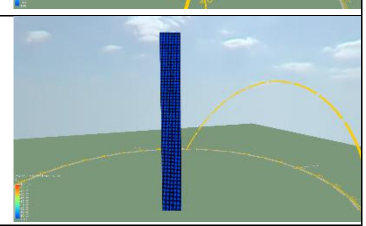
8%		
6%		

4.5.4.2 Thermal performance-based design

Thermal performance based-design is the second strategy to be implemented for developing the kinetic system of the selected case study. Therefore, after generating a parametric model that represent the kinetic behaviour of the building in reference to the selected WWR that was analysed to propose kinetic scenarios that result in reducing the energy consumption of the building, a study on the sun exposure of the building was generated through IES VE. Table 35 shows the sun cast images of the case study generated in the same proposed dates and timing of the previously discussed WWR analysis which are; 21^{st} Dec, 21^{st} June and 21^{st} March, each scenario at 8:30 AM, 12:30 PM and 17:30 PM to indicate the areas that would require more shading and less WWR.

Table 35: Dubai Frame Sun Exposure

Dubai Frame- Sun Exposure			
Date/ Time	8:30 AM	12:30 PM	17:30 PM
	South		
21st Mar			
21st Jun			
21st Dec			
	North		
21st Mar			
21st Jun			

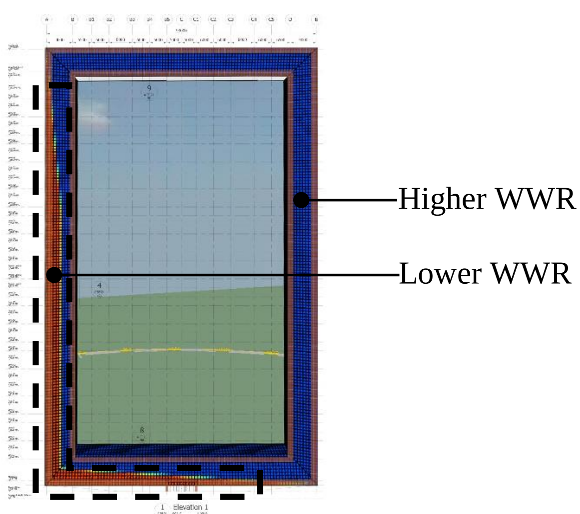
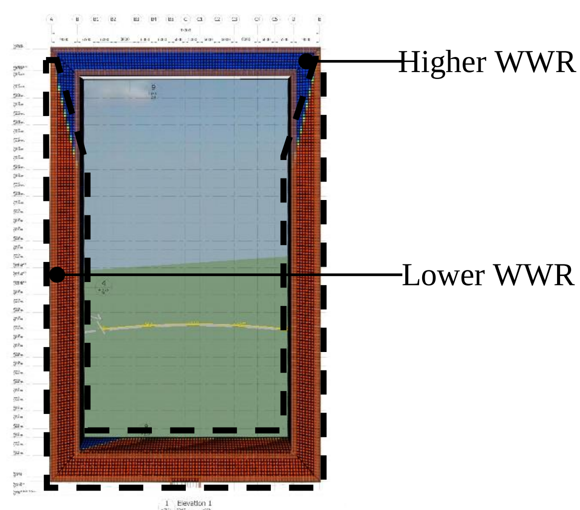
21st Dec			
	East		
21st Mar			
21st Jun			
21st Dec			
	West		
21st Mar			
21st Jun			
21st Dec			

In Table 35, the high exposure of the South façade can be found in 21st of March at 12:30 PM and 17: 30 PM and in 21st of December at 8:30 AM and 12:30 PM. However, the South façade is having partially high exposure in most of its area in 21st of June at 12:30 PM and in some areas in 21st of March at 8:30 AM and in 21st of June at 17:30 AM.

On the other hand, in the North façade, a high sun exposure can be found in 21st of June at 8:30 AM. Whereas in the East façade a high exposure is identified in the three selected dates; 21st of March, 21st of June and 21st of March at 8:30 AM and 12:30 AM. However, in the West façade, a high exposure is found in 21st of March and in 21st of June at 17:30 PM.

Based on the data discussed in this strategy, lower WWR should be allocated to the areas that have higher sun exposure in each façade in reference to the sun cast images generated in Table 35. Moreover, some facades would have a combination of two WWR when there is partial sun exposure in some of its areas. For example, in the South façade, the areas of higher exposure would have a higher WWR where the geometrics would close in a higher percentage than the areas with less exposure as described in Table 36. This would be used in a cumulative process to select the kinetic scenarios in stage 4.

Table 36: An example for the Sun exposure analysis of the South façade to be used for WWR selection.

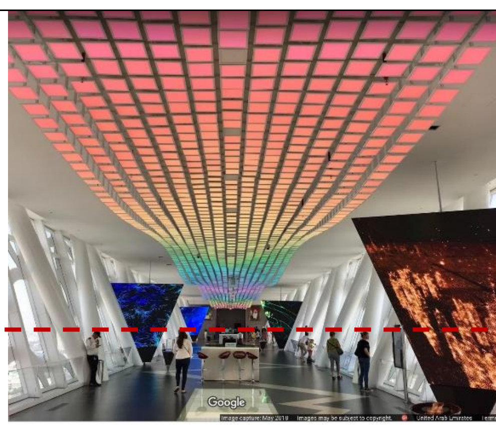
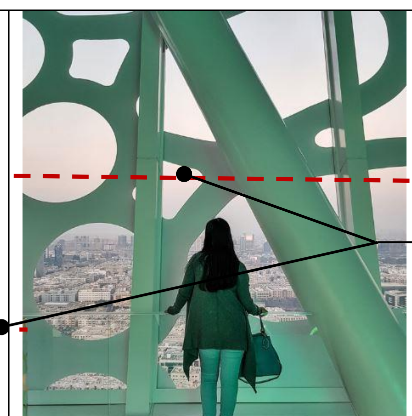
21st of March/ 8:30 AM	**21st of June/ 5:30 PM**
	

4.5.4.3 Aesthetic performance-based design

The third strategy, that is expected to affect the proposed kinetic behaviour of the building, is the aesthetic performance based-design. As mentioned in the case study selection, the building, Dubai Frame, is considered an iconic building in Dubai where it is located to overlook the new Dubai from one side and the old Dubai from one side. Therefore, the functionality of the building should be taken into consideration for the areas that would close and open in reference to the proposed WWR. These areas can be identified in reference to human scale of the building visitors especially in the Viewing Bridge of the building.

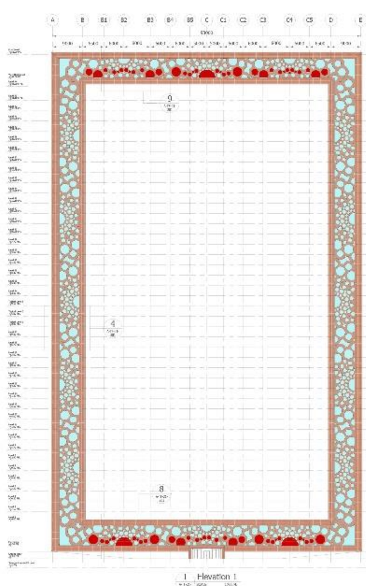
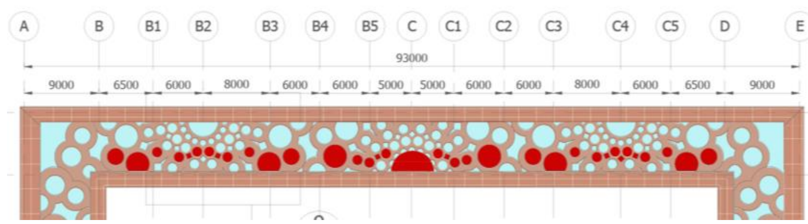
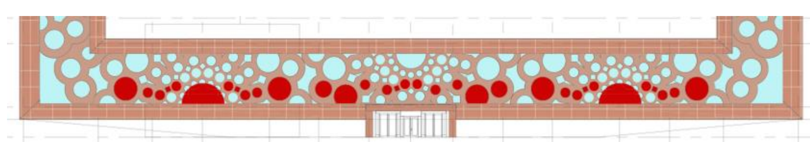
Table 37 shows some images of the Viewing Bridge and the Mezzanine Floor. It should be noted that there are many exhibitions stands located in the Mezzanine Floor which are already blocking the view in these areas. However, WWR of the geometrics located in the height of the human scale for the Bridge and the Mezzanine would need to remain open to allow the users to enjoy the view and the purpose of the building to achieve the required aesthetic values.

Table 37: Dubai Frame Viewing Bridge and Mezzanine exhibition stands.

Bridge		 Human Scale
Mezannine		 Exhibition Stands

Following the previously mentioned aesthetic values that will affect the kinetic behaviour of the building, a zoom in of the highlighted areas that would need to remain open in respect to the functionality of the building is highlighted in red in Table 38. This behaviour should be applied on both North and South façade for the Viewing Bridge and the Mezzanine Floor as the new Dubai would be viewed from the South side and the old city from the North side. Moreover, the geometrics are selected between 1200 MM to 2500 MM except for the geometrics that start from the finish floor level.

Table 38: the implementation of the aesthetic performance based-design strategy on both South and North façade.

Base case abstract (South and North façade)	**Geometries that would need to remain open in respect to the functionality of the building**
	 Viewing Bridge
	 Mezzanine Floor

4.5.5 Stage Five: Selecting the kinetic scenarios

After discussing the impact of the proposed kinetic strategies to achieve the targeted performance levels of energy, thermal and aesthetic values, a selection of each façade kinetic behaviour will be collated and described in this stage to end up with an optimal design for the proposed kinetic system. Therefore, to be able to investigate the proposed kinetic system using IES VE simulation software, nine scenarios will be selected for this assessment in reference to the selected dates and timings that was used throughout the analysis process of the base case and the selected kinetic strategies in stage 3.

To select the kinetic scenarios of each façade, a cumulative process will be implemented to describe the impact of each strategy on its kinetic movement that will be represented in different WWRs. The process will identify how each façade WWR is going to be adjusted to reach to an optimal design (optimal WWR) that fulfil the required levels of energy, thermal and aesthetic values. Figure 67 describes this process:

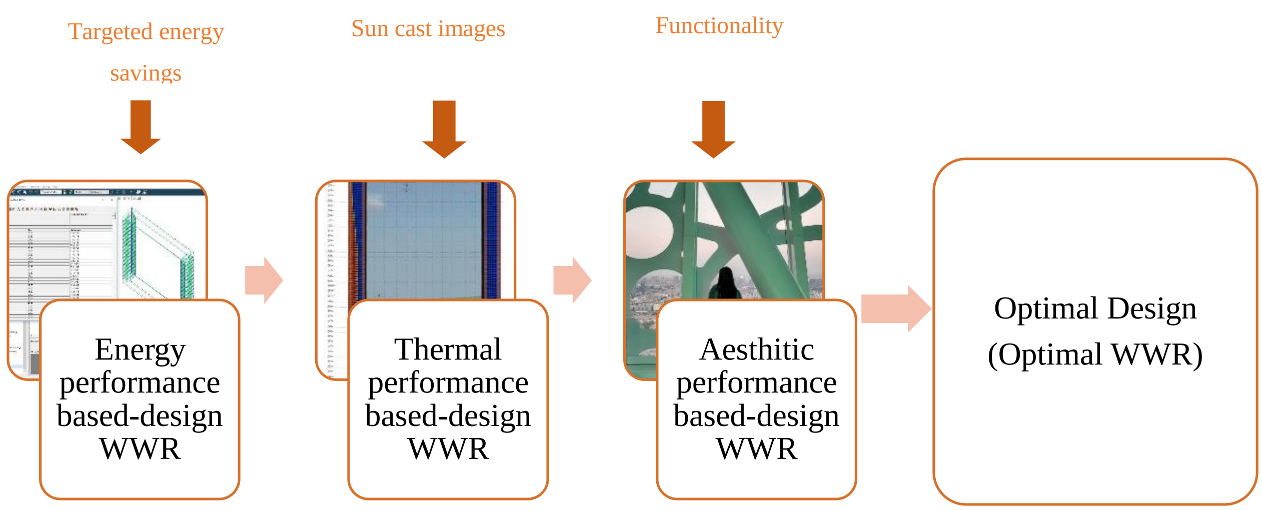


Figure 67: The cumulative process for selecting the optimal design (optimal WWR)

The targeted energy reduction was used as a set point of selecting each façade WWR in reference to the resulted energy saving that was indicated in the literature, which ranges from 20% to 50%. However, in this kinetic typology, Elzeyadi (2017) mentioned that a total reduction in energy consumption would reach up to 38%. Table 39 shows the targeted energy savings percentage of each scenario that was calculated based on the conducted cooling loads that was analysed in stage three. The average targeted energy saving of the proposed kinetic behaviour when the kinetic system is proposed based on the first strategy; Energy performance-based design Strategy would reach up to 31%.

Table 39: Selected WWR based on Energy performance-based design Strategy

Kinetic Scenario/ Simulation	**Selected WWR based on Energy performance-based design Strategy**				**Total targeted energy savings**
	South façade	North façade	East façade	West façade	
SIM01	15%	10%	6%	8%	32%
SIM02	30%	15%	10%	12%	28%
SIM03	10%	20%	8 %	6%	26%
SIM04	25%	15%	6%	8%	42%
SIM05	30%	15%	10%	10%	43%
SIM06	10%	10%	8 %	8 %	39%
SIM07	10%	25%	6%	12%	18%
SIM08	20%	15%	12 %	10%	25%
SIM09	10%	10%	10 %	6%	22%
AVE					31%

After selecting the kinetic behaviour based on the energy performance-based design strategy, each scenario WWR was adjusted based on the conducted sun cast images that represent the sun exposure of the proposed scenarios to achieve the required daylighting levels based on the thermal performance-based design Strategy. The proposed WWR was reduced by 5% in the areas that had higher exposure in South and North facades. However, the in East and West façade, it was reduced by 2%. Table 40 highlights the areas that was adjusted in respect to the thermal performance-based design Strategy.

For example, in the East façade, the proposed WWR was the least ratio during sunrise timing in Sim 01, SIM04 and SIM07. However, in the West façade, the least ratio was proposed in SIM03, SIM06 and SIM09 during sunset.

Table 40: Selected WWR based on Thermal performance-based design Strategy

Kinetic Scenario/ Simulation	**Selected WWR based on Thermal performance-based design Strategy**			
	South façade	North façade	East façade	West façade
SIM01	**14%**	10%	6%	8%
SIM02	**25%**	15%	**8%**	12%
SIM03	**10%**	20%	**10%**	**6%**
SIM04	25%	**10%**	6%	8%
SIM05	**28%**	15%	**8%**	10%
SIM06	10%	10%	**10%**	**6%**
SIM07	**10%**	25%	6%	12%
SIM08	**15%**	15%	**10%**	10%
SIM09	10%	10%	**12%**	6%

The last process implemented to achieve the optimal kinetic behaviour of the selected case study was the Aesthetic performance-based design strategy, as the areas of the geometrics that need to remain open was calculate in AutoCAD to be added to the void area used in conducting both North and South façade WWR. The functionality of the building is one of the main parameters that was used during this process to proof to designer that kinetic systems can also be adapted with the building architecture. Table 41 highlights the proposed WWR that was adjusted based on the Aesthetic performance-based design strategy to result in an optimal WWR that describes the kinetic behaviour of each scenario.

Table 41: Optimal WWR as a Result of the Aesthetic Performance-Based Design Strategy

Kinetic Scenario/ Simulation	**Optimal WWR**			
	South façade	North façade	East façade	West façade
SIM01	**16%**	**12%**	6%	8%
SIM02	**26%**	**17%**	8%	12%
SIM03	**12%**	**22%**	10%	6%
SIM04	**26%**	**12%**	6%	8%
SIM05	**29%**	**17%**	8%	10%
SIM06	**12%**	**12%**	10%	6%
SIM07	**12%**	**26%**	6%	12%
SIM08	**17%**	**17%**	10%	10%
SIM09	**12%**	**12%**	12%	6%

At the end of this stage, each scenario WWR is adjusted in AutoCAD and collated in respect to the optimal WWR to enable the researcher to investigate the performance levels in terms of energy consumption and daylighting levels through IES VE software in real life conditions as a result of all the strategies and the kinetic mechanisms conducted in the process of developing the proposed kinetic system.

CHAPTER FIVE

RESULTS AND DISCUSSION

Chapter 5 Results and discussion

5.1 Introduction

In this chapter, the optimal kinetic scenarios of SIM 1 to SIM 9 will be simulated through IES VE software to investigate the impact of the proposed kinetic system on the selected case study energy and daylighting levels.

In addition, cooling and electricity loads will be indicated for the base case, which is the building with its existing fixed shading, then the new shading design, which is called the abstract, and the kinetic behaviour of the building envelop in each scenario, SIM 1-9. After that, results will be identified in a matrix to get the figures of the targeted annual energy savings to achieve a highly efficient building that is more flexible to adapt to the external environment.

Moreover, daylighting levels will be described and compared between the base case and the kinetic system for SIM1 to SIM 9 scenarios to evaluate the simulation results and provide a kinetic system that enhance the existing indoor environment by avoiding sun glare and solar gains throughout the building.

5.2 Energy consumption results

Energy consumption results compare the data of the following conditions:

1. **Base case:** Existing Building.
2. **Base case Abstract:** the new proposed design of the façade that is described in chapter four for selecting the kinetic typology in Table 19 and Table 20. This scenario presents the proposed condition of the building in its static movement that would be proposed from 17:30 PM to 8:30 AM.
3. **SIM1-9:** Present the time and date of the selected scenarios to test the performance of the kinetic movement as highlighted in Table 14.

The comparison between the base case, abstract and the proposed kinetic system for each scenario; SIM 1 to SIM 9 in terms of electricity and cooling loads is presented in Figure 68. On the other hand, Figure 69 illustrates the difference of all the proposed scenarios from SIM 1-9. The highest electricity loads savings are achieved in SIM 8 with 27.02%. However, the lowest electricity loads saving is shown clearly in SIM 7 with 11.4%. Figure 70 presents the proposed electricity savings for SIM 1-9 which results in an average of 23%.

Figure 68: Total room cooling loads and electricity result for SIM 1-9

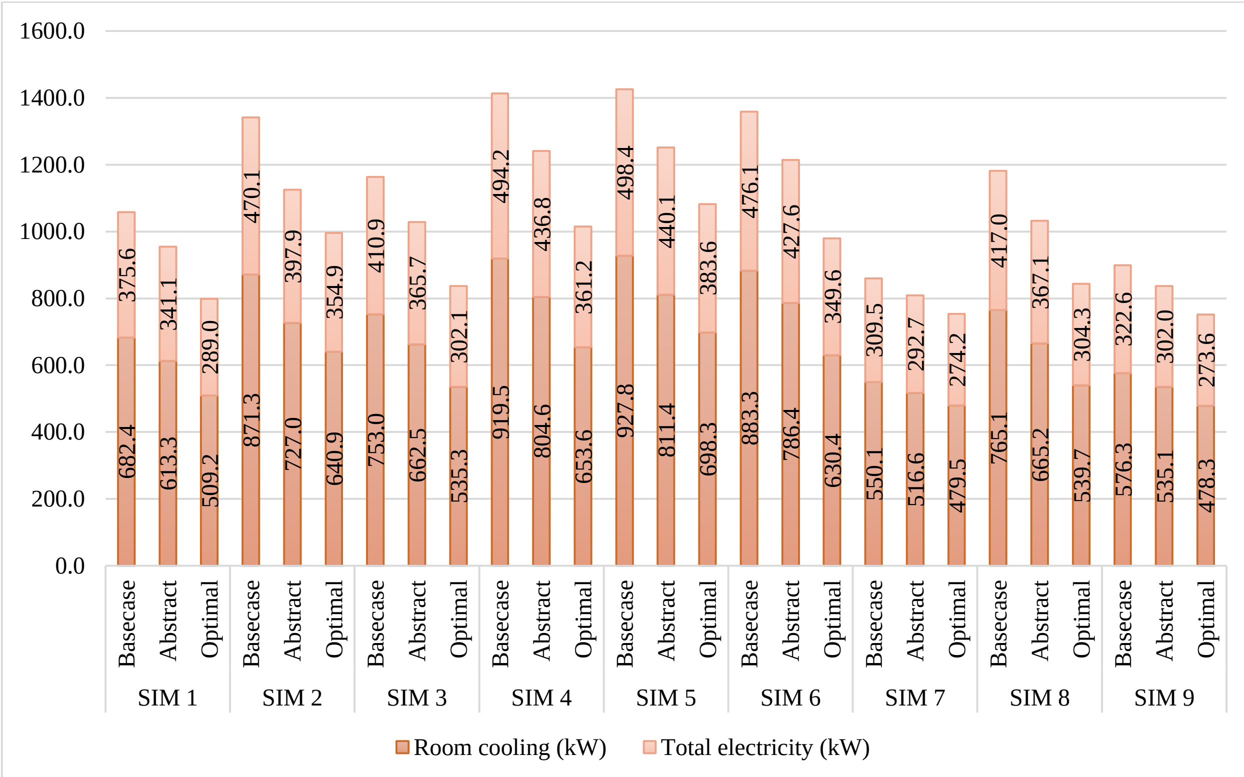


Figure 69: Total Electricity & Cooling Loads for SIM 1-9

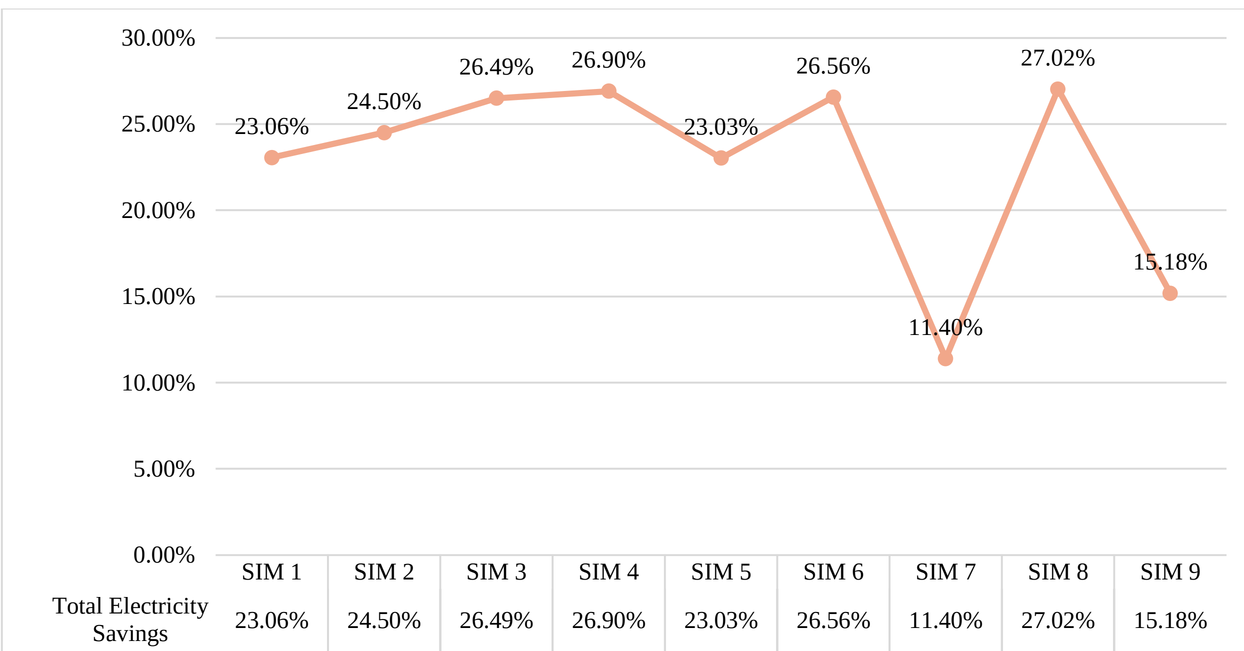


Figure 70: Total Electricity Savings for SIM 1-9

After comparing the result of each scenario, an investigation of the average performance of the proposed kinetic system is conducted between the time period from 8:30 AM to 17:30 PM to test the performance of the proposed kinetic system behaviour during the day.

The process of conducting this analysis is obtained by measuring the energy performance levels of each scenario from SIM1-9 from 8:30 AM to 17:30 PM in March, June and December as shown in Table 42 . After that, SIM 1, 4 and 7, which is implemented at 8:30 AM is tested for the period from 8:30 AM to 10:30 AM as presented in Figure 71. Moreover, SIM 2, 5 and 8 which is designed for 12:30 PM is applied on the period from 11:30 AM to 13:30 PM as presented in Figure 72. On the other hand, SIM 3, 6 and 9 that is selected for 17:30 PM is used for the period from 14:30 PM to 17:30 PM as indicated in Figure 73.

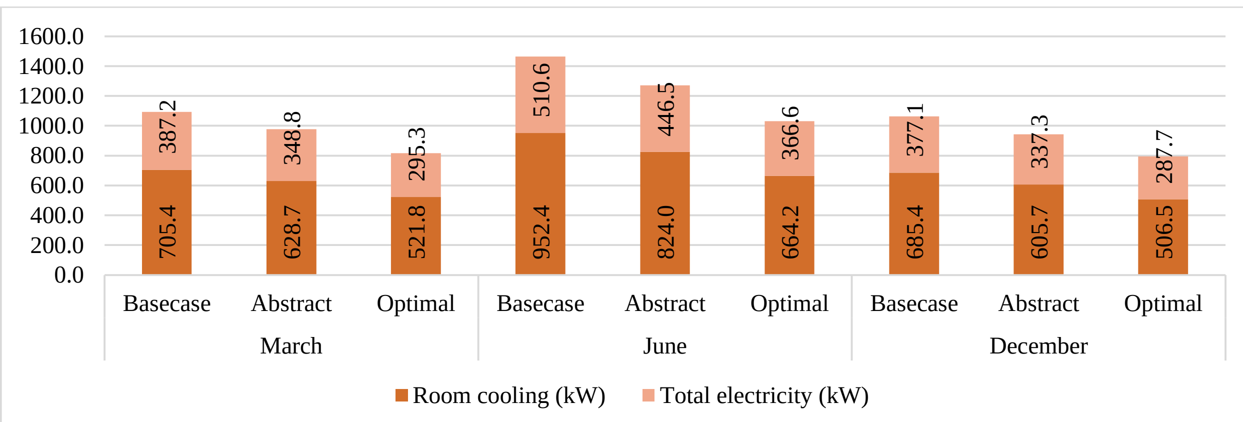


Figure 71: The average total electricity & cooling loads for SIM 1,4,7 for the period from 8:30 AM to 10:30 AM

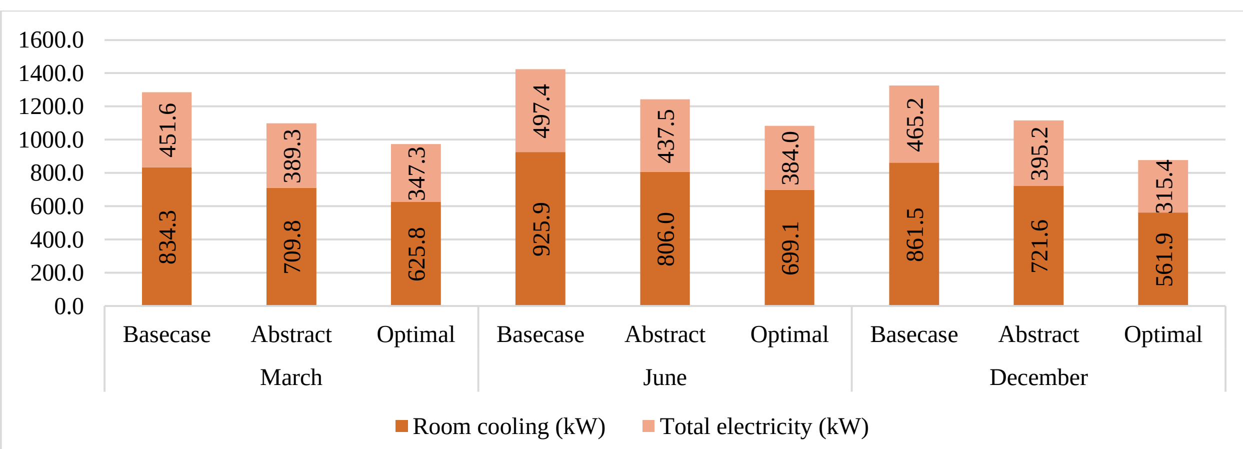


Figure 72: The average total electricity & cooling loads for SIM 2,5,8 for the period from 11:30 AM to 13:30 PM

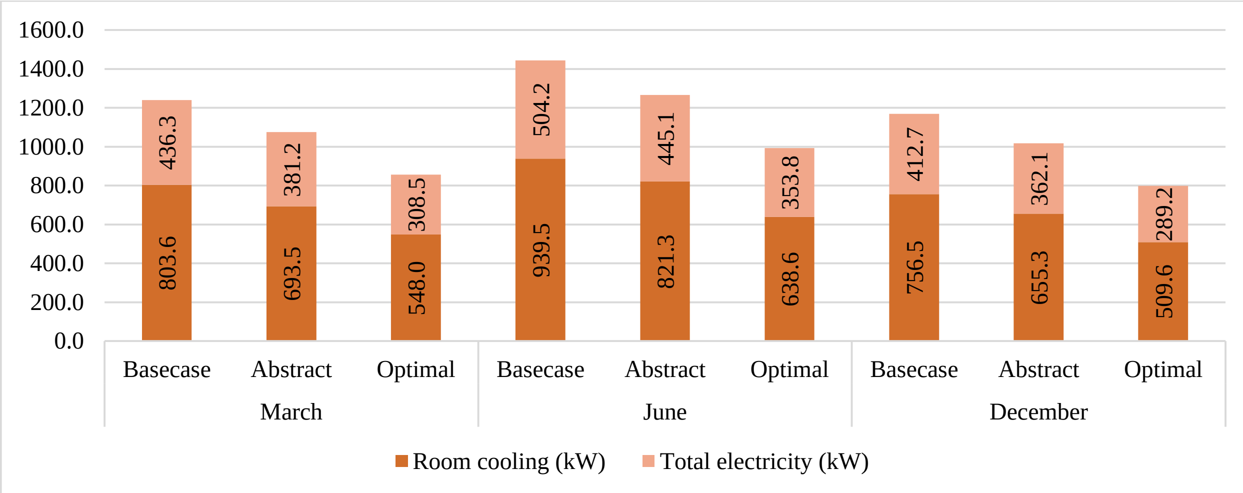


Figure 73: The average total electricity & cooling loads for SIM 3,6,9 for the period from 14:30 PM to 17:30 PM

The average electricity savings of the optimal design from 8:30 AM to 17:30 PM is presented in Figure 74 below. The highest savings are shown in December in the period from 11:30 AM to 13:30 PM with 32.2%. However, June has the lowest electricity savings with an average of 22.8% in the period from 11:30 AM to 13:30 PM. The average of the total electricity savings equal 27% for March, June and December from 8:30 AM to 17:30 PM.

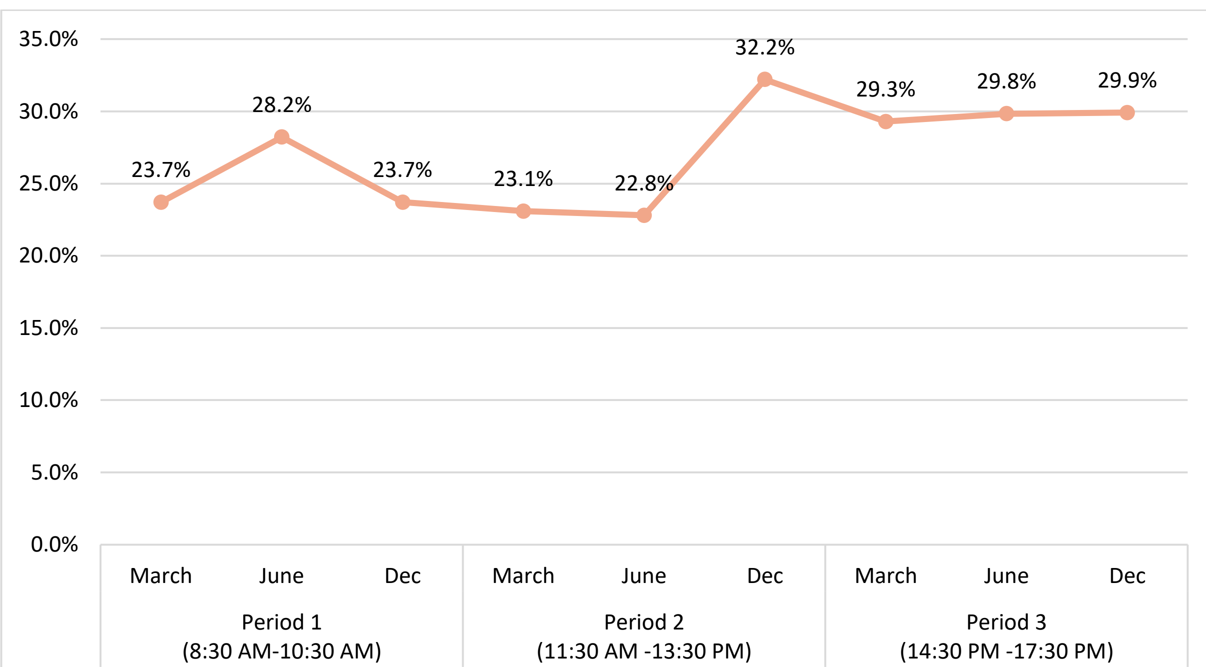


Figure 74: The average electricity savings of the optimal design from 8:30 AM to 17:30 PM

Table 42: The average total electricity & cooling loads for SIM 1-9 for the period from 8:30 AM to 17:30 PM

March										
Time	**Base case**		**Abstract**		**SIM 1**		**SIM 2**		**SIM 3**	
	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)
8:30 AM	640.94	354.91	585.85	327.36	506.35	287.61				
9:30 AM	705.39	387.13	629.75	349.31	521.62	295.25				
10:30 AM	770.00	419.44	670.54	369.70	537.50	303.19				
11:30 AM	810.87	439.87	694.93	381.90			612.28	340.58		
12:30 PM	836.16	452.52	710.56	389.71			626.67	347.77		
13:30 PM	856.01	462.44	723.79	396.33			638.33	353.60		
14:30 PM	865.05	466.96	731.34	400.11					560.88	314.88
15:30 PM	848.60	458.74	722.99	395.93					557.59	313.23
16:30 PM	796.43	432.65	690.46	379.67					546.85	307.86
17:30 PM	704.44	386.66	629.17	349.02					526.87	297.87
June										
Time	**Base case**		**Abstract**		**SIM 4**		**SIM 5**		**SIM 6**	
	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)
8:30 AM	925.59	497.23	808.63	438.75	655.72	362.30				
9:30 AM	967.41	518.14	834.93	451.90	667.35	368.11				
10:30 AM	964.18	516.53	828.57	448.72	669.63	369.25				
11:30 AM	926.61	497.74	806.79	437.83			694.86	381.87		

12:30 PM	913.32	491.10	800.97	434.92			693.20	381.04		
13:30 PM	937.79	503.33	810.35	439.61			709.16	389.02		
14:30 PM	963.70	516.29	830.75	449.81					641.48	355.18
15:30 PM	971.91	520.39	843.31	456.09					644.66	356.77
16:30 PM	946.03	507.45	830.26	449.56					640.85	354.86
17:30 PM	876.32	472.60	780.80	424.83					627.52	348.20
December										
Time	**Base case**		**Abstract**		**SIM 7**		**SIM8**		**SIM 9**	
	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)	Room cooling (kW)	Total electricity (kW)
8:30 AM	589.41	329.14	542.82	305.84	483.41	276.14				
9:30 AM	691.38	380.13	610.00	339.43	508.30	288.59				
10:30 AM	775.28	422.08	664.31	366.59	527.82	298.35				
11:30 AM	836.97	452.92	704.97	386.92			557.25	313.06		
12:30 PM	869.22	469.05	726.63	397.75			563.47	316.17		
13:30 PM	878.37	473.62	733.10	400.99			564.87	316.87		
14:30 PM	869.79	469.33	728.62	398.74					529.12	299.00
15:30 PM	826.73	447.80	702.62	385.74					522.45	295.66
16:30 PM	727.44	398.16	638.23	353.55					505.15	287.01
17:30 PM	601.96	335.42	551.89	310.38					481.53	275.20

Furthermore, annual energy savings are investigated by applying the data provided for each scenario throughout the year. This process is conducted by using the data for march to present Spring and Autumn months presented by SIM 1,2 and 3 and the data resulted in June for Summer months presented in SIM 4,5 and 6, whereas December results are tested for Winter months and presented by SIM 7,8 and 9.

In order to test the annual performance of the kinetic system, the new design abstract results are used for the period with static movement that range from 17:30 PM to 8:30 PM. However, daily periods are calculated for each month in reference to the previous measurements illustrated in Table 42. Table 43 below illustrated the process of analysing the annual results of SIM 1-9.

Table 43: The data used to measure the annual performance of the kinetic system

Period/ Month	Jan.	Feb.	Mar	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct	Nov.	Dec.
8:30 AM to 10:30 AM	SIM 7	SIM 7	SIM 1	SIM 1	SIM 1	SIM 4	SIM 4	SIM 4	SIM 1	SIM 1	SIM 1	SIM 7
11:30 AM to 13:30 PM	SIM 8	SIM 8	SIM 2	SIM 2	SIM 2	SIM 5	SIM 5	SIM 5	SIM 2	SIM 2	SIM 2	SIM 8
14:30 PM to 17:30 PM	SIM 9	SIM 9	SIM 3	SIM 3	SIM 3	SIM 6	SIM 6	SIM 6	SIM 3	SIM 3	SIM 3	SIM 9
17:30 PM to 8:30 AM	Abstract											

As a result of calculating the annual performance of the proposed kinetic system in reference the process illustrated in Table 43, a summary of the total electricity and cooling loads are presented in Table 44 to identify the difference between the base case and the optimal design of the proposed kinetic behaviour, which is described in Figure 75 for the annual cooling loads and Figure 76 for the annual electricity loads in the base case, abstract and the optimal kinetic design.

Table 44: A summary of the annual electricity and cooling loads for the base case, abstract and the optimal design

Month	Base case		Abstract		Optimal Design	
	Room cooling (MW)	Total electricity (MW)	Room cooling (MW)	Total electricity (MW)	Room cooling (MW)	Total electricity (MW)
Jan	430.5	240.9	392.9	222.1	351.8	201.5
Feb	418.0	232.1	377.8	212.0	336.3	191.3
Mar	475.6	263.4	432.4	241.8	396.7	224.0
Apr	506.0	277.8	458.3	253.9	420.0	234.8
May	572.8	312.0	515.6	283.4	470.9	261.1
Jun	579.2	314.4	521.5	285.6	475.6	262.6
Jul	618.5	334.9	554.5	302.9	506.1	278.7
Aug	624.4	337.8	559.0	305.1	511.4	281.3
Sep	584.8	317.2	523.1	286.3	480.0	264.8
Oct	564.0	307.6	504.7	278.0	461.6	256.4
Nov	494.9	272.3	445.6	247.6	407.9	228.8
Dec	453.4	252.3	412.6	231.9	370.5	210.8
Total	6322.13	3462.73	5698.02	3150.65	5188.83	2896.07

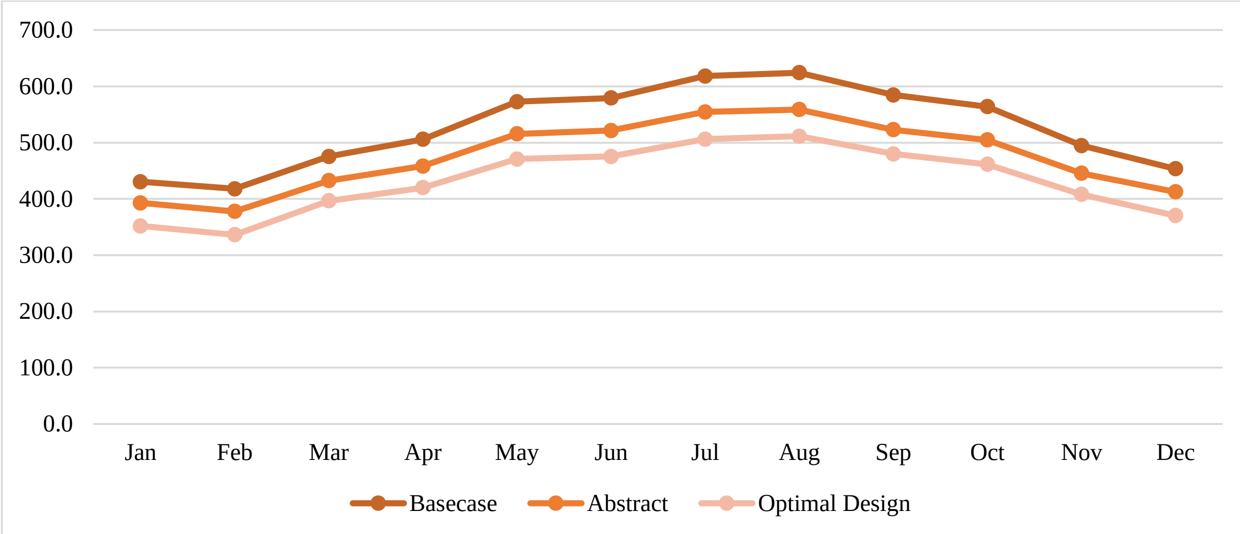


Figure 75: The annual cooling loads (MW) for the base case, abstract and the optimal kinetic design

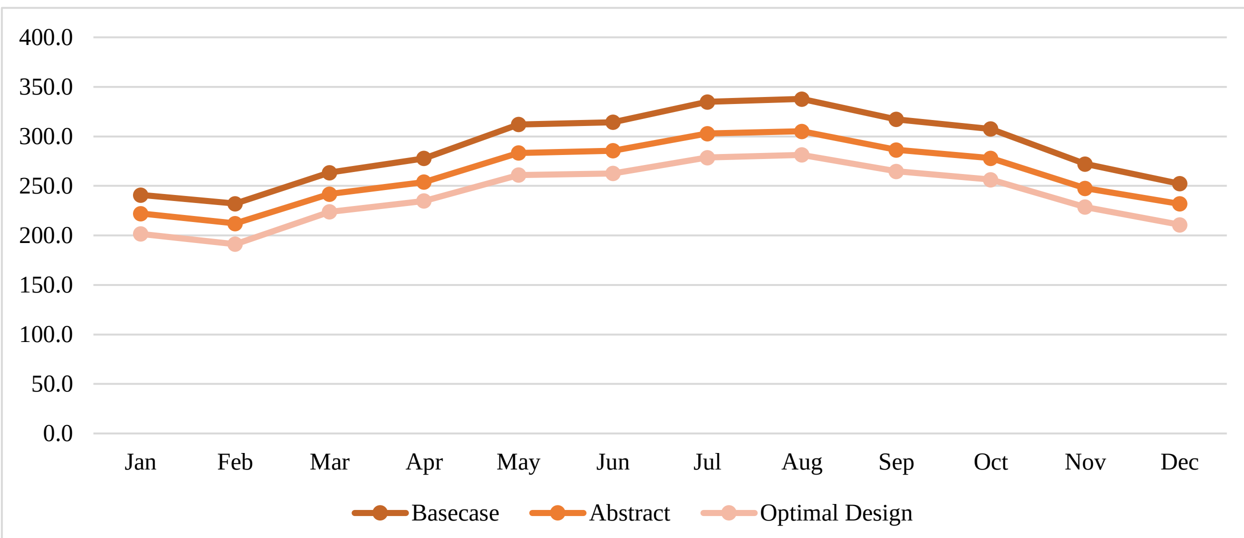


Figure 76: The annual electricity loads (MW) for the base case, abstract and the optimal kinetic design

On the other hand, Table 45 shows the annual energy savings of each month presented in a total reduction of to 18% for cooling loads and 16% for total electricity loads. The highest energy savings are indicated in February. However, the lowest reduction in energy savings is identified in March and April as described in Figure 77.

Table 45: the optimal design annual energy savings

Month	Optimal Design Vs. Base case	
	Room cooling (MW)	Total electricity (MW)
Jan	18%	16%
Feb	20%	18%
Mar	17%	15%
Apr	17%	15%
May	18%	16%
Jun	18%	16%
Jul	18%	17%
Aug	18%	17%
Sep	18%	17%
Oct	18%	17%
Nov	18%	16%
Dec	18%	16%
Total	18%	16%

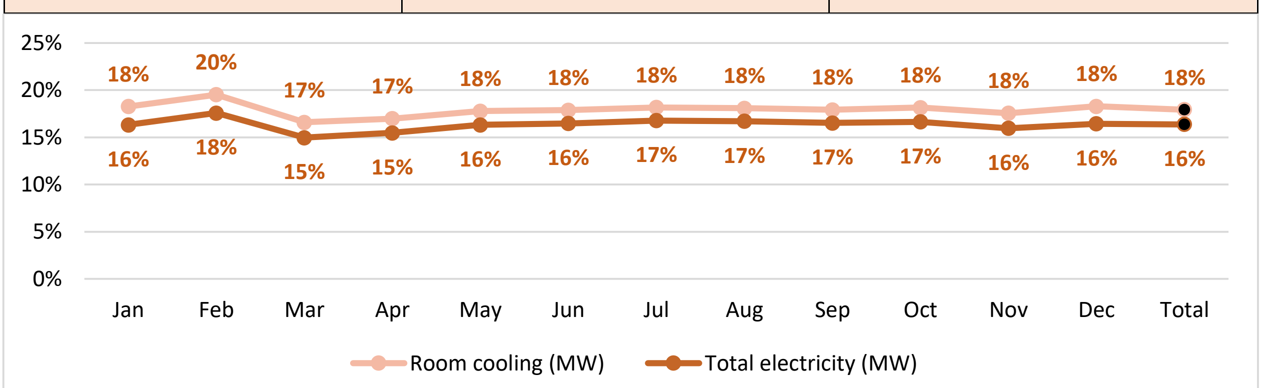


Figure 77: The optimal design annual energy savings

5.3 Cost analysis

In this section, the cost savings will be identified in reference to the conducted energy bills that was given by Dubai Municipality maintenance department. based on the cost of these bills, the cost of every KW equal 0.441 Dhs. Which is used to calculate the annual cost of the total energy consumption for the base case and the optimal design in Table 46 below.

Table 46: Total energy bills

Month	Base case Energy Bills **(**Dhs)	Optimal Design Energy Bills (Dhs)
Jan	106,221	88,874
Feb	102,366	84,361
Mar	116,162	98,762
Apr	122,502	103,547
May	137,599	115,131
Jun	138,658	115,804
Jul	147,675	122,896
Aug	148,983	124,072
Sep	139,892	116,769
Oct	135,664	113,081
Nov	120,063	100,884
Dec	111,281	92,983
Total	1,527,066	1,277,165

Moreover, Figure 78 compares the annual cost in the base case, base case abstract and the optimal design of the kinetic system. A total savings in the cost of the building energy bills would reach up to 249,901 Dhs as presented in Figure 79.

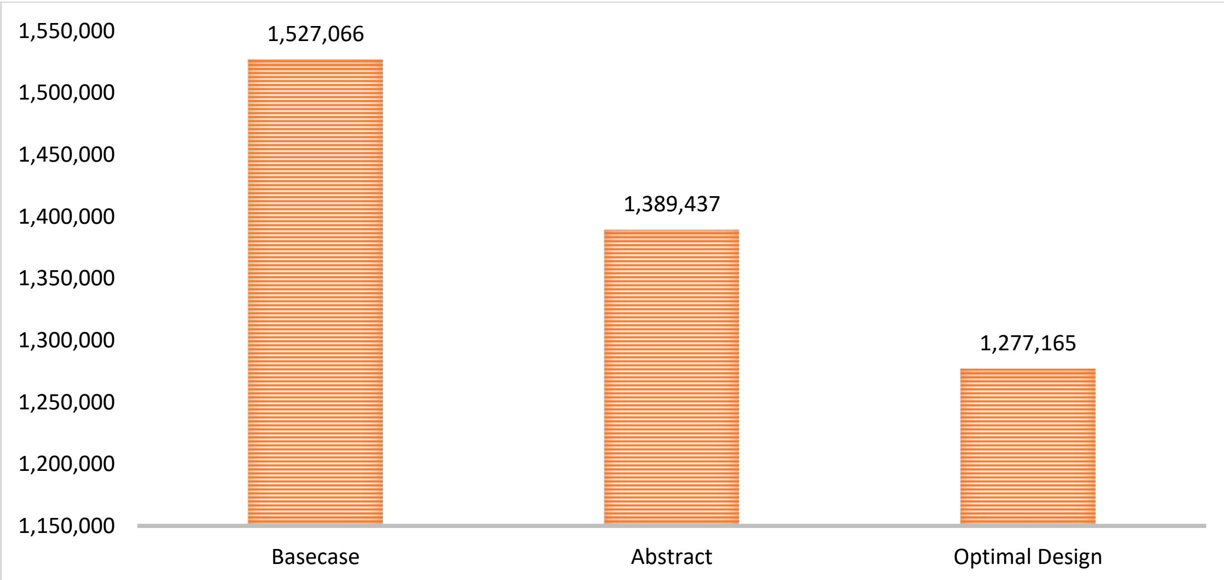


Figure 78: Annual cost of energy consumption for the base case, abstract and the optimal design.

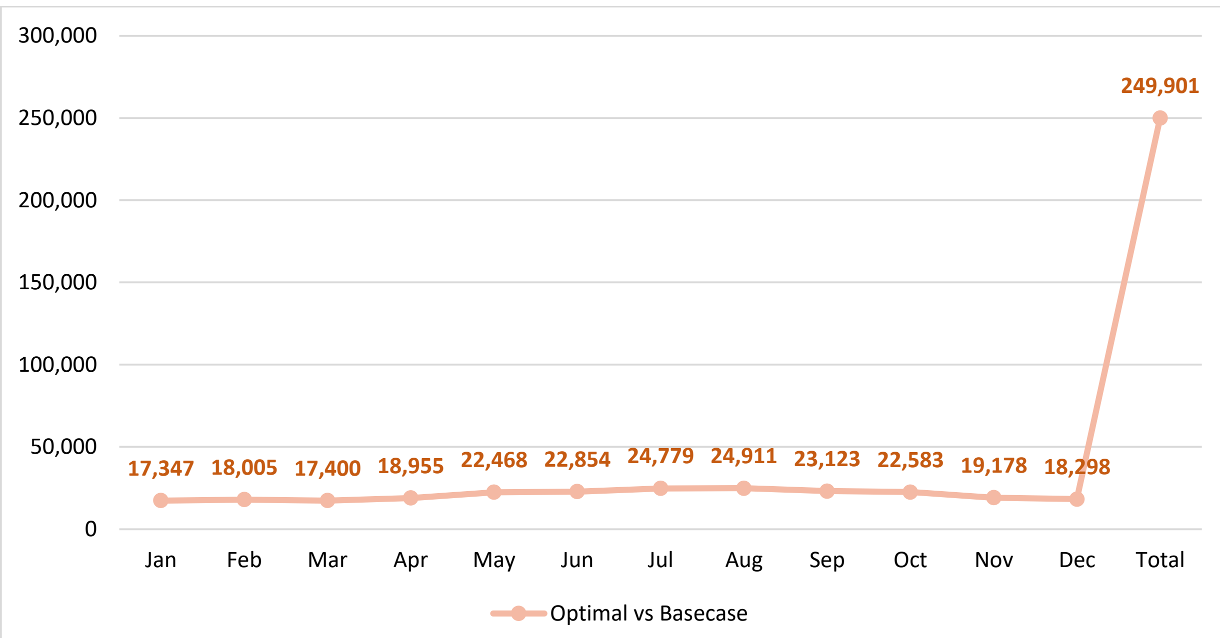


Figure 79: Total cost savings of the proposed kinetic system

5.4 Daylighting results

In this section, indoor illuminance levels due to daylighting will be evaluated to measure the effectives of the proposed kinetic scenarios SIM 1 to SIM 9 with respect to the base case illuminance levels using simulation tools, IES VE using RADIANCE plugin in this case.

Accordingly, difference in in the illuminance levels are identified in each scenario as an average of the daylight distribution in East and West side for the Mezzanine Floor and the Viewing Bridge in the selected case study.

Illuminance levels represent the amount of daylight levels incident on the surfaces. Table 47 list the standards of daylight illuminance levels that will be used to measure the implications of proposed kinetic scenarios (Nabil & Mardaljevic 2006).

Table 47: Daylight Illuminance Standards, (Nabil & Mardaljevic 2006)

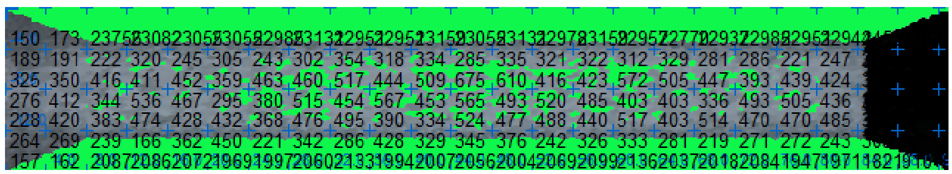
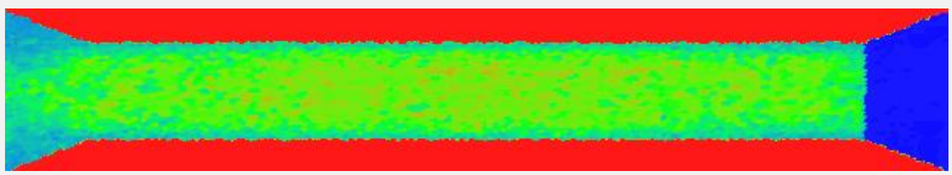
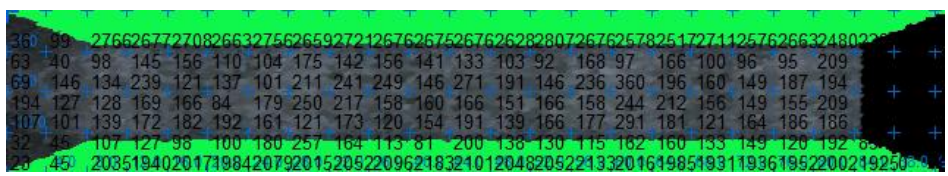
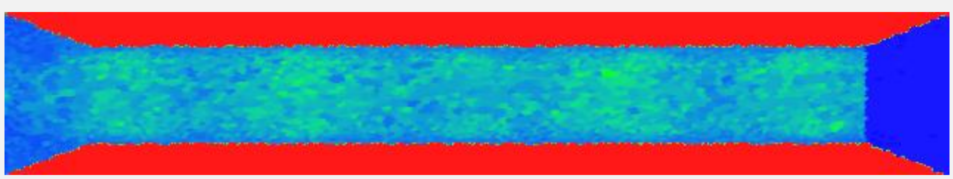
Average Daylight Illuminance	**Energy implications**
100 lux	Insufficient either to be the sole source of illumination or to contribute significantly to artificial lighting.
100–500 lux	Effective either as the sole source of illumination or in conjunction with artificial lighting.
500–2000 lux	It is perceived either as desirable or at least tolerable.
> 2000 lux	Visual and thermal discomfort

The following tables from Table 48 to Table 65 shows a comparison between the base case and the optimal design for the Mezzanine Floor and the Viewing Bridge illuminance and Radiance contour levels of SIM 1-9. Moreover, and average of illuminance lux levels are indicated.

Illuminance plans highlight the areas that have a daylight illuminance above 500 lux in light green. However, radiance contour images show the glare that is caused by the reflection of sunlight with a threshold of 500 lux.

In SIM 1, Table 48 shows the area of sun glare that is reduced significantly in the Viewing Bridge optimal design as illuminance levels are reduced from 1139.13 to 966.88 lux. On the other hand, in Table 49, in the Mezzanine Floor, illuminance levels are reduced from 809.55 to 360.94.

Table 48: SIM 1- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Viewing Bridge

Base case	Illuminance Plan	
	Radiance Contour Plan	
Optimal design	Illuminance Plan	
	Radiance Contour Plan	
Comparison	**Basecase**	**Optimal design**

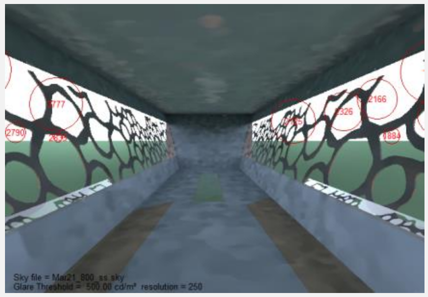
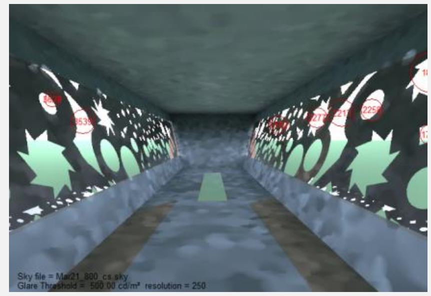
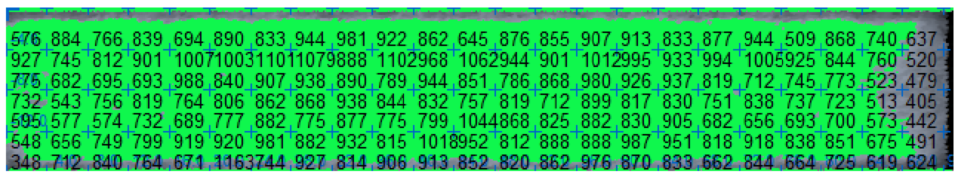
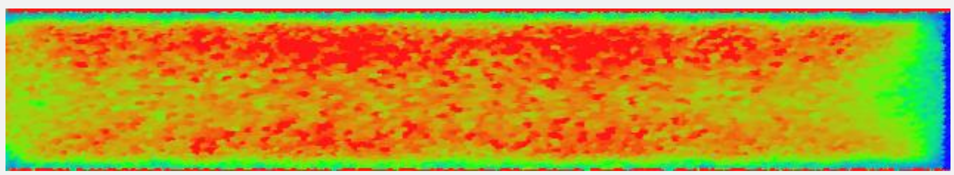
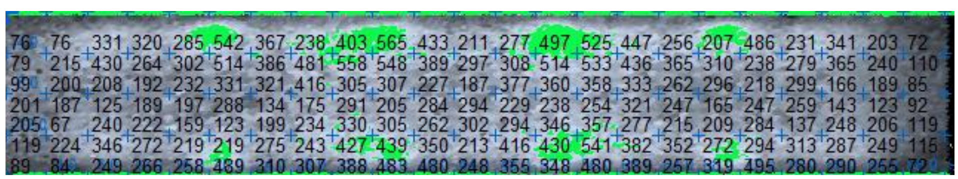
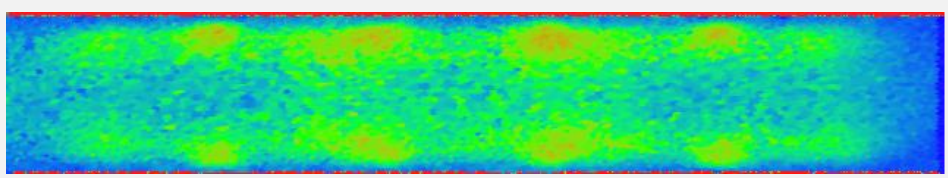
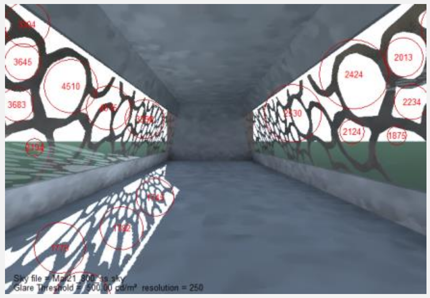
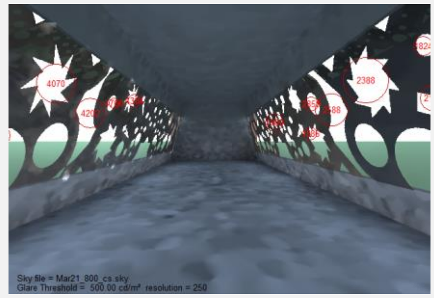
Luminance Image (to show façade pattern and geometrics openings)		
AVE Illuminance levels (lux)	1139.13 Lux	966.88 Lux

Table 49: SIM 1- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Mezzanine Floor

Base case	Illuminance Plan	
	Radiance Contour Plan	
Optimal design	Illuminance Plan	
	Radiance Contour Plan	
Comparison	**Basecase**	**Optimal design**

Luminance Image (to show façade pattern and geometrics openings)		
AVE Illuminance levels (lux)	809.55 Lux	360.94 Lux

In SIM 2, in Table 50, although the area of sun glare in the illuminance plans are reduced, the average illuminance lux levels remain almost the same as it is reduced from 1577 to 1506 lux in the Viewing Bridge. However, in Table 51, in the Mezzanine Floor, illuminance levels are reduced from 1219 to 824 lux. It should be noted that in this scenario, the proposed WWR in the South façade is 26% which is resulted from the targeted overall energy savings of this scenario.

Table 50: SIM 2- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Viewing Bridge

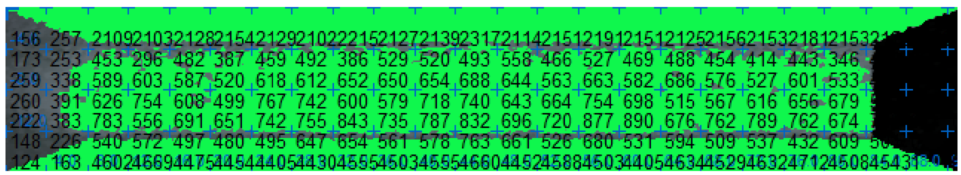
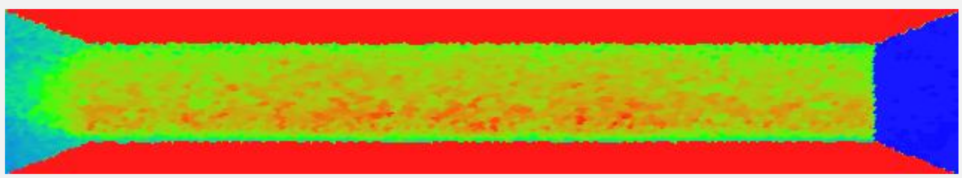
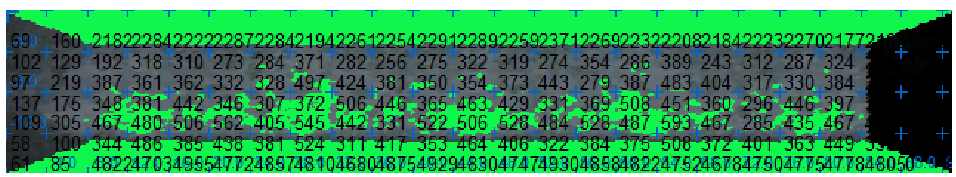
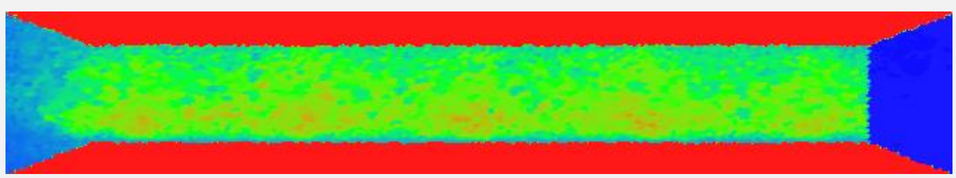
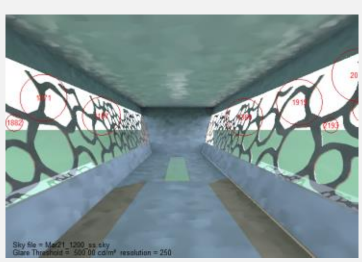
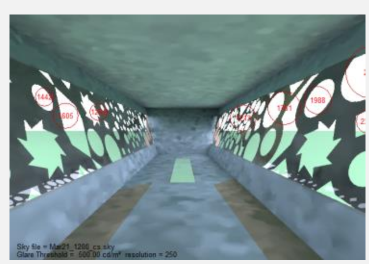
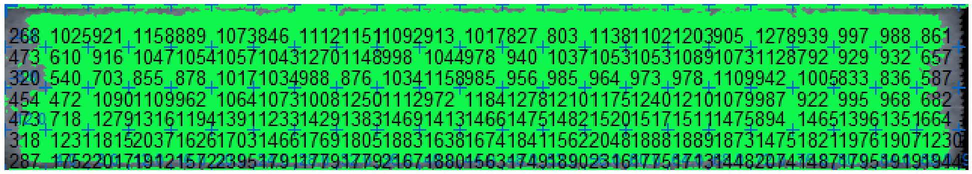
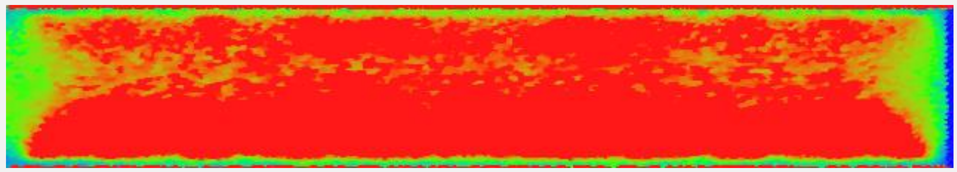
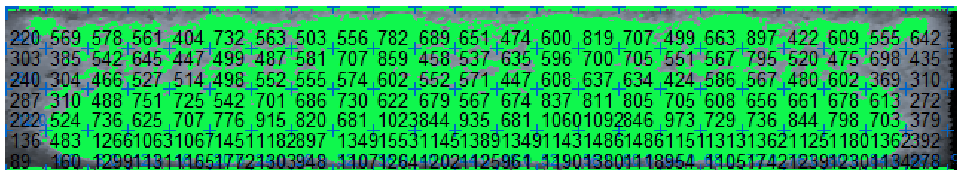
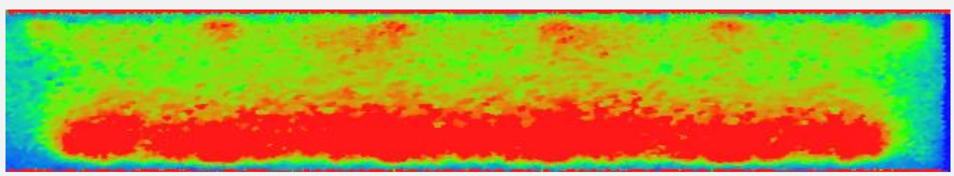
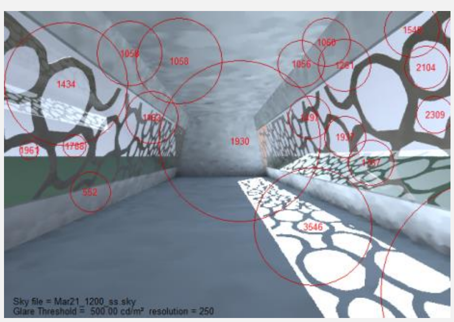
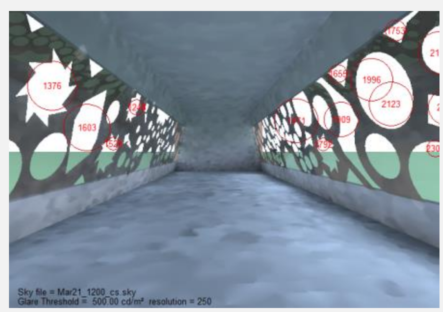
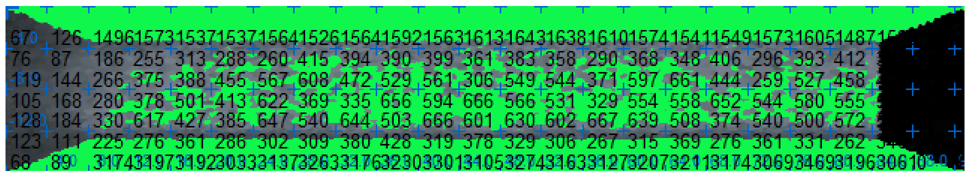
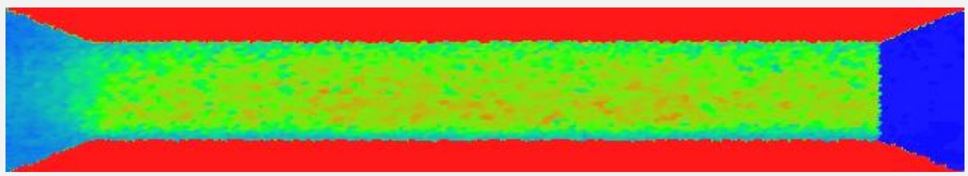
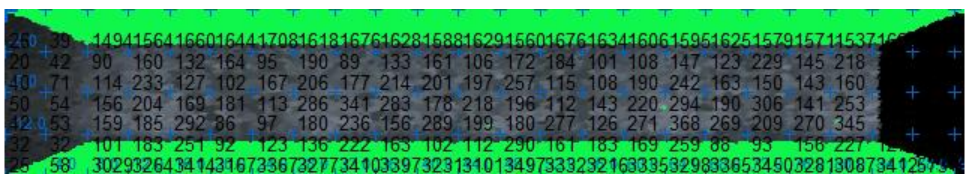
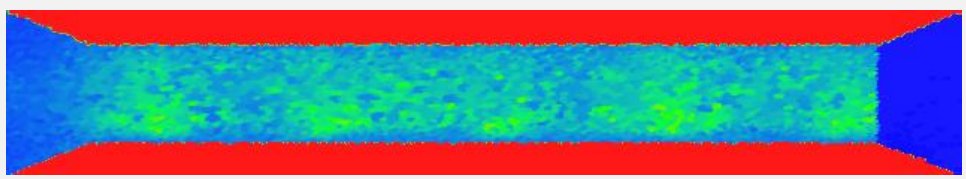
<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td></td><td></td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>1576.69 Lux</td><td>1506.30 Lux</td></tr>
</table>

Table 51: SIM 2- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Mezzanine Floor

Base case	Illuminance Plan		
	Radiance Contour Plan		
Optimal design	Illuminance Plan		
	Radiance Contour Plan		
Comparison		**Basecase**	**Optimal design**
Luminance Image (to show façade pattern and geometrics openings)			
AVE Illuminance levels (lux)		1218.78 Lux	824.00 Lux

In SIM 3, the highest illuminance levels are shown in the edges of the Viewing Bridge illuminance plans in Table 52. Nevertheless, illuminance levels are dropped from 1110.65 lux to 999.63 lux. On the other hand, in the Mezzanine Floor, in Table 53, the area of sun glare in the radiance contour plans are reduced significantly from 855.95 lux to 314.22.

Table 52: SIM 3- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Viewing Bridge

Base case	Illuminance Plan	
	Radiance Contour Plan	
Optimal design	Illuminance Plan	
	Radiance Contour Plan	

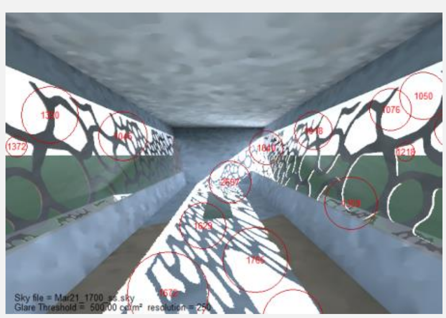
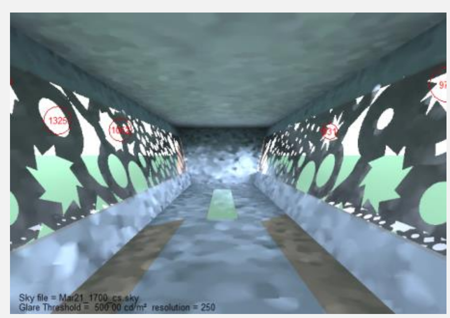
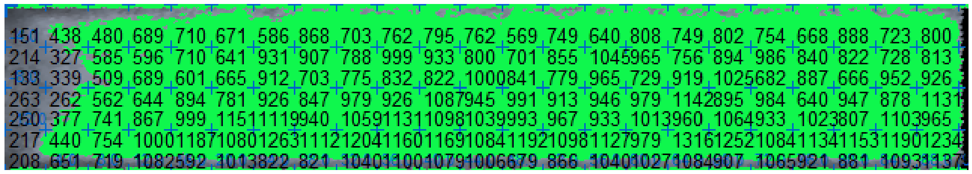
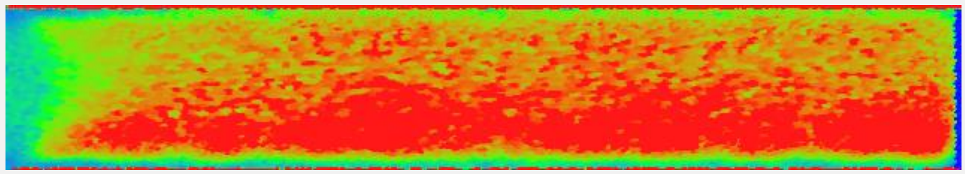
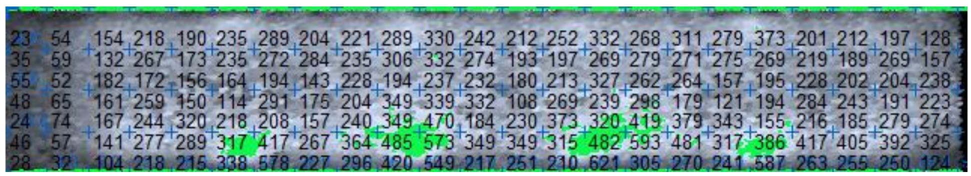
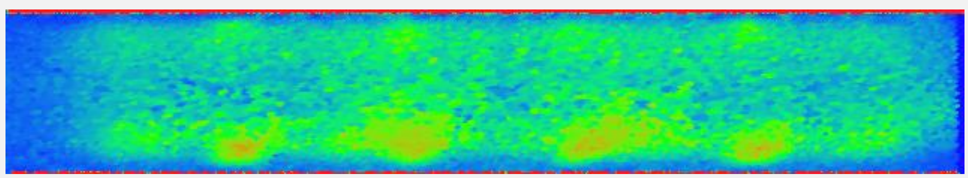
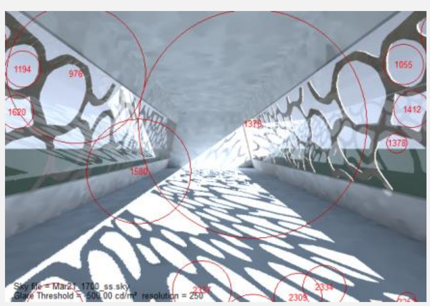
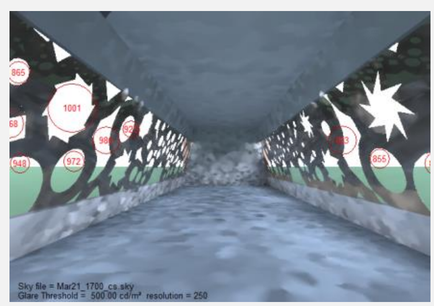
Comparison	**Basecase**	**Optimal design**
Luminance Image (to show façade pattern and geometrics openings)		
AVE Illuminance levels (lux)	1110.65 Lux	999.63 Lux

Table 53: SIM 3- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Mezzanine Floor

Base case	Illuminance Plan	
	Radiance Contour Plan	
Optimal design	Illuminance Plan	
	Radiance Contour Plan	

Comparison	Basecase	Optimal design
Luminance Image (to show façade pattern and geometrics openings)		
AVE Illuminance levels (lux)	855.95 Lux	314.22 Lux

In SIM 4, average illuminance levels are dropped from 1435.55 lux to 1299 lux in the Viewing Bridge as indicated in Table 54. The reduction in the area of Illuminance levels above 500 lux are clearly illustrated in the optimal design illuminance plans. However, Table 55 present the enhancement in the average illuminance lux levels in the Mezzanine Floor where it is dropped from 1094.49 to 543 lux.

Table 54: SIM 4- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Viewing Bridge

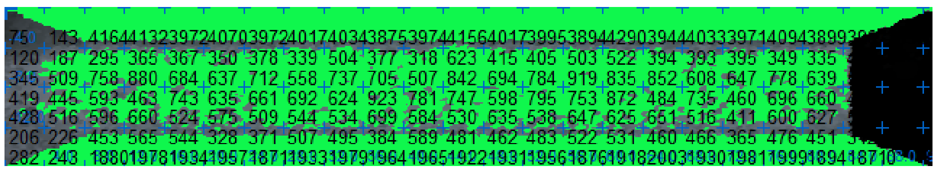
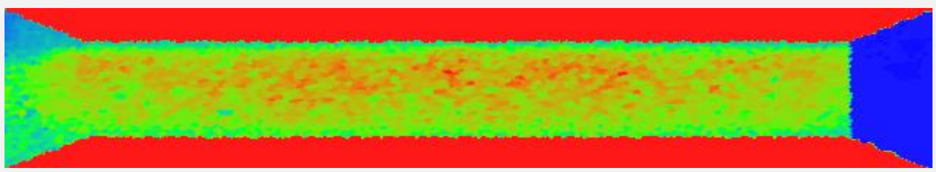
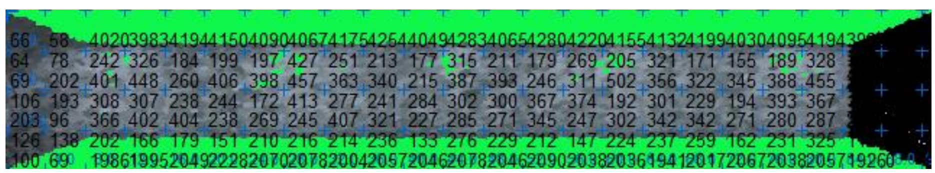
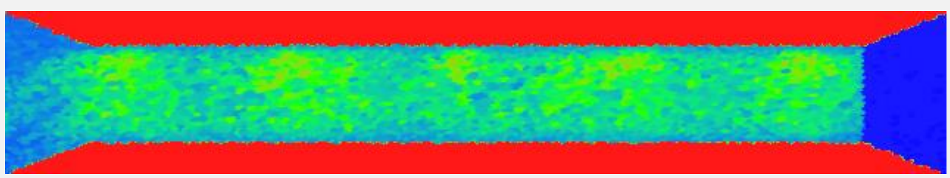
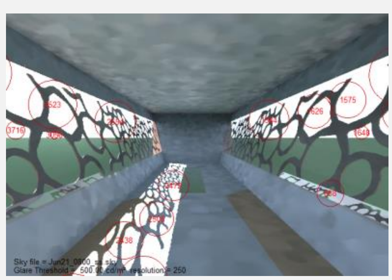
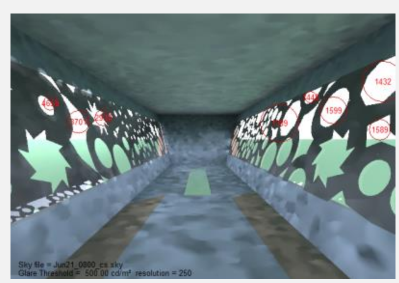
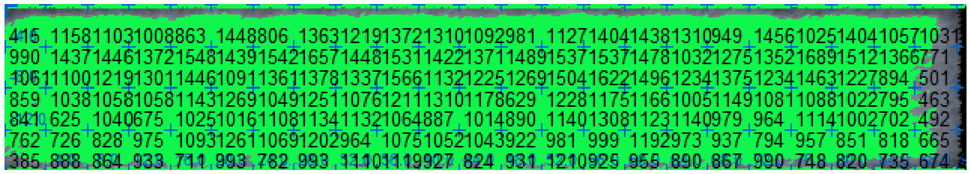
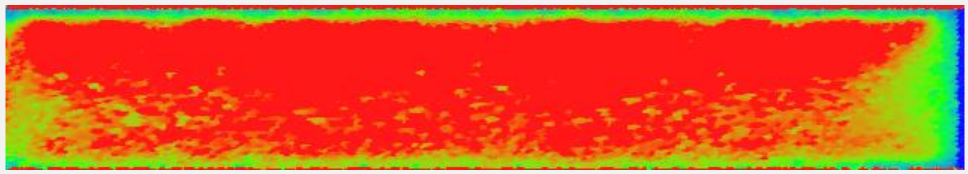
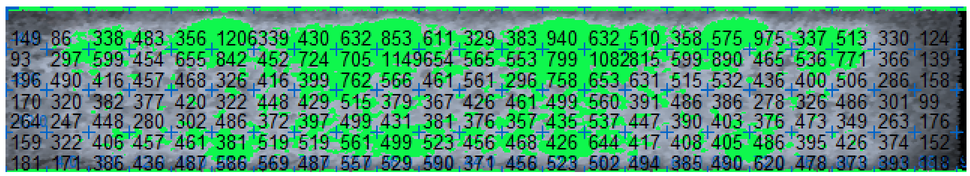
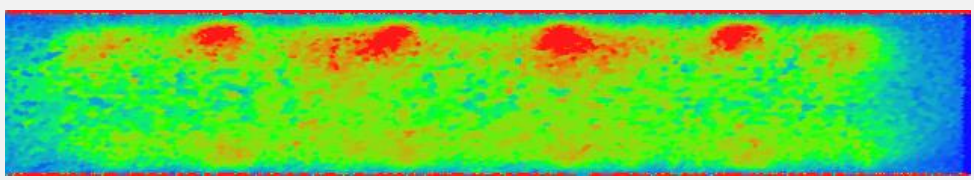
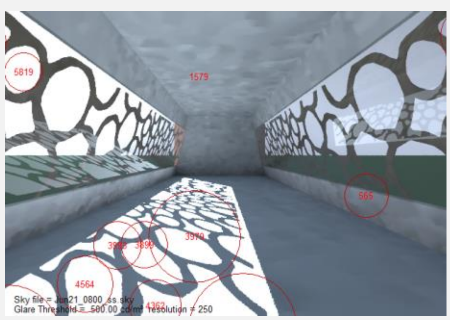
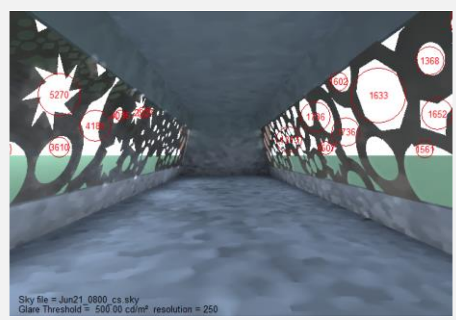
Base case	Illuminance Plan	
	Radiance Contour Plan	
Optimal design	Illuminance Plan	
	Radiance Contour Plan	
Comparison	**Basecase**	**Optimal design**
Luminance Image (to show façade pattern and geometrics openings)		
AVE Illuminance levels (lux)	1435.55 Lux	1299.10 Lux

Table 55: SIM 4- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Mezzanine Floor

<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td></td><td></td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>1094.49 Lux</td><td>543.05 Lux</td></tr>
</table>

In SIM 5, the average illuminance lux levels remain almost the same in the Viewing Bridge as presented in Table 56 where it is dropped by approximately 170 lux. However, in Table 57, in the Mezzanine Floor, illuminance levels are dropped by approximately 1000 lux. On the other hand, SIM 5 proposed WWR act among the highest of 29% WWR in the South façade as a result from the targeted overall energy savings of this scenario.

Table 56: SIM 5- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Viewing Bridge

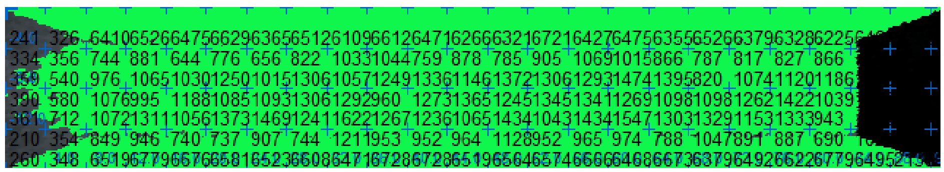
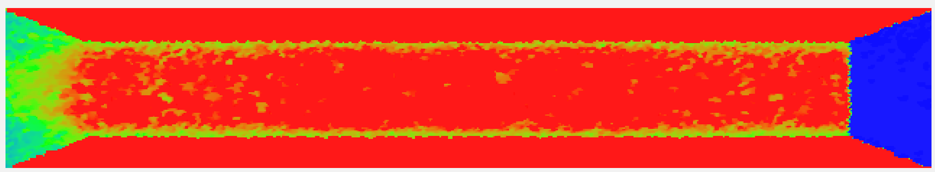
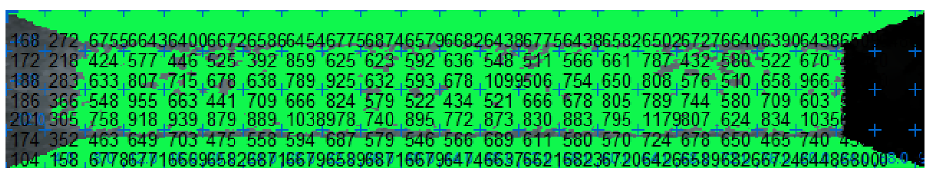
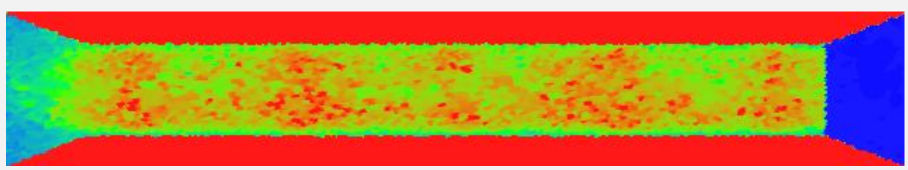
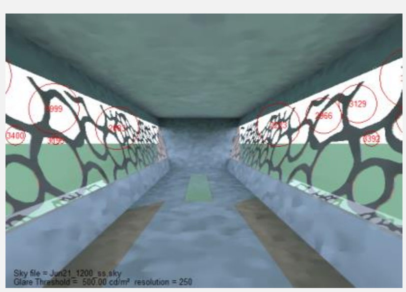
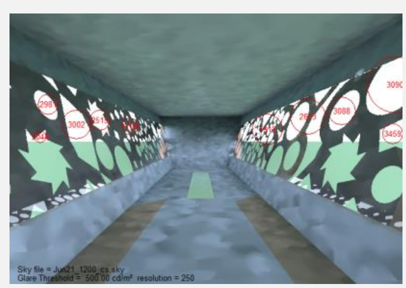
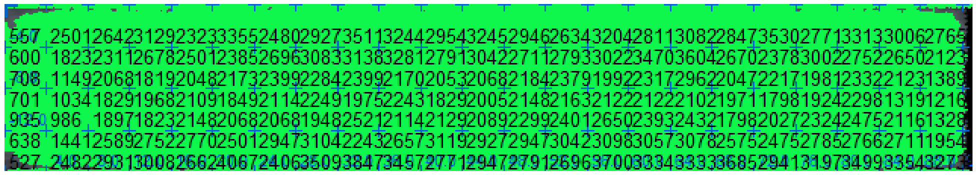
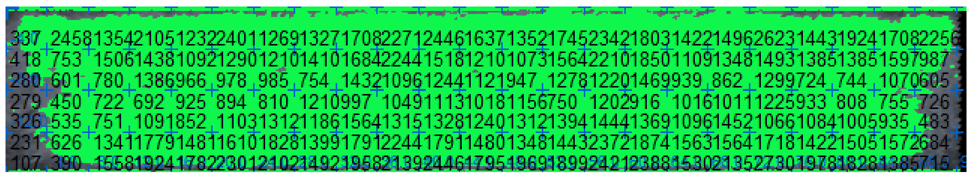
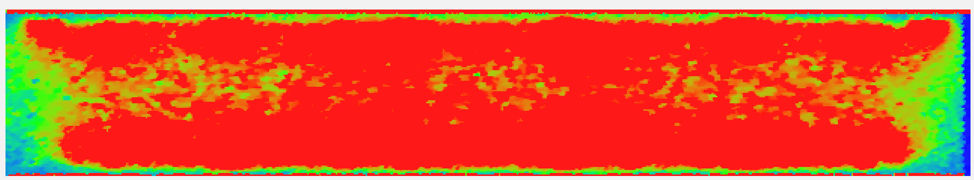
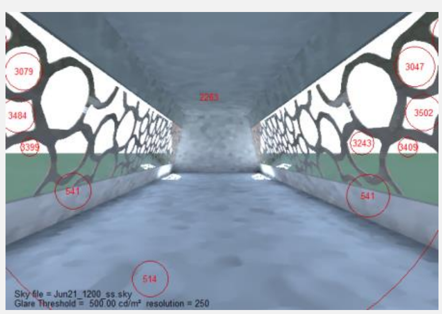
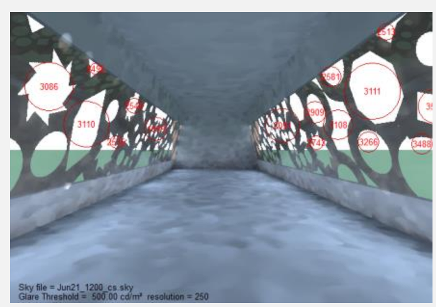
<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td></td><td></td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>3090.93 Lux</td><td>2927.89 Lux</td></tr>
</table>

Table 57: SIM 5- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Mezzanine Floor

<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td></td><td></td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>2520.89 Lux</td><td>1544.55 Lux</td></tr>
</table>

In SIM 6, Table 58 shows a reduction the area of sun glare in the Viewing Bridge where illuminance levels are dropped from 1201.16 to 1072.72 lux. On the other hand, in Table 59 illuminance levels are reduced from 906.21 to 371.78 in the Mezzanine Floor.

Table 58: SIM 6- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Viewing Bridge

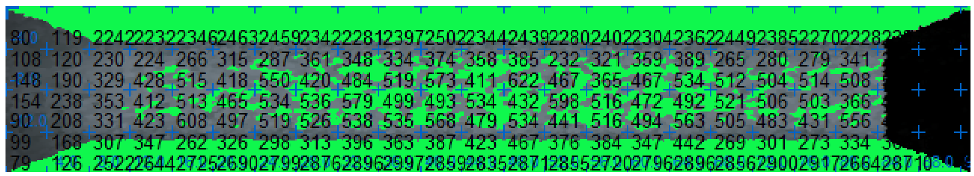
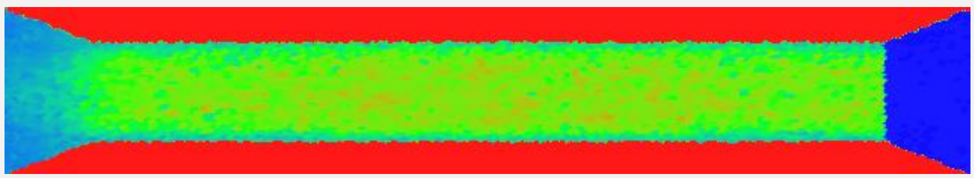
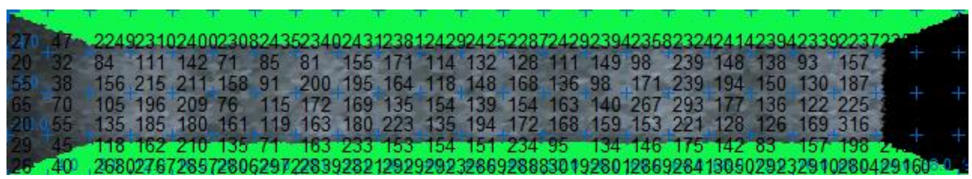
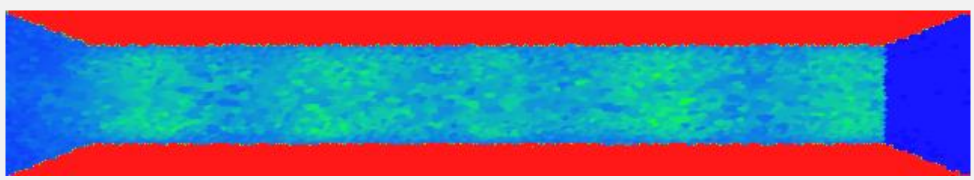
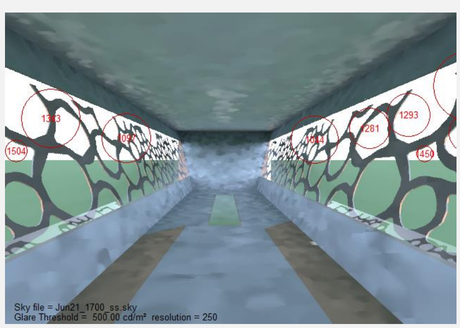
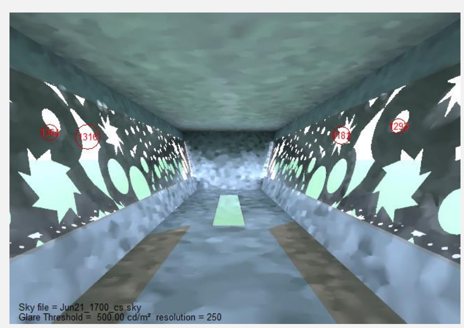
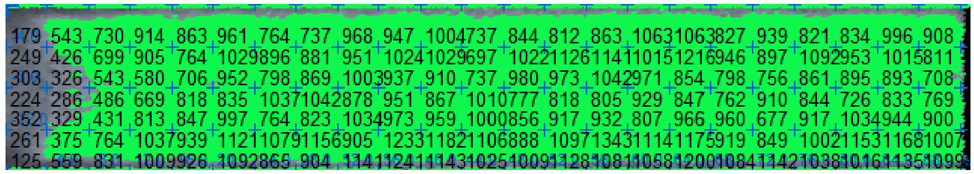
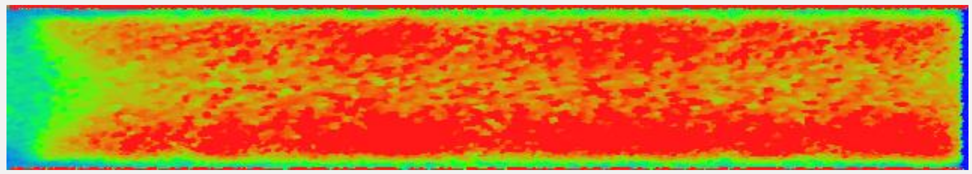
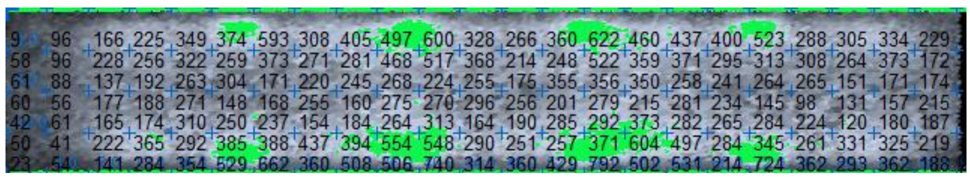
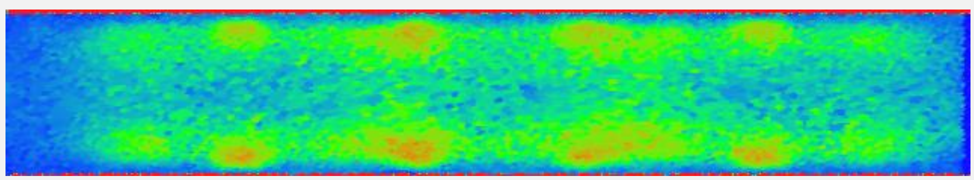
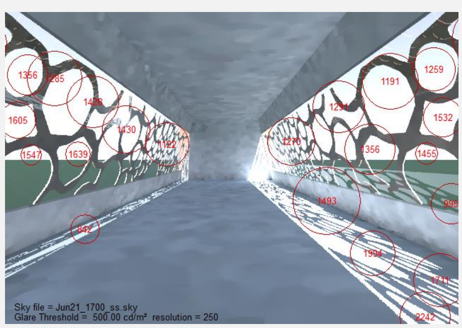
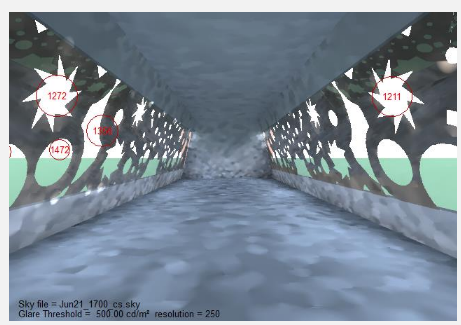
<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td></td><td></td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>1201.16 Lux</td><td>1072.72 Lux</td></tr>
</table>

Table 59: SIM 6- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Mezzanine Floor

<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td></td><td></td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>906.21 Lux</td><td>371.78 Lux</td></tr>
</table>

SIM 7 results in a significant reduction in both the area of sun glare and illuminance levels with an average reduction of 1370 lux as presented in Table 60. Further, in the Mezzanine Floor, illuminance levels are dropped from 596.48 to 257.72 lux as shown in Table 61.

Table 60: SIM 7- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Viewing Bridge

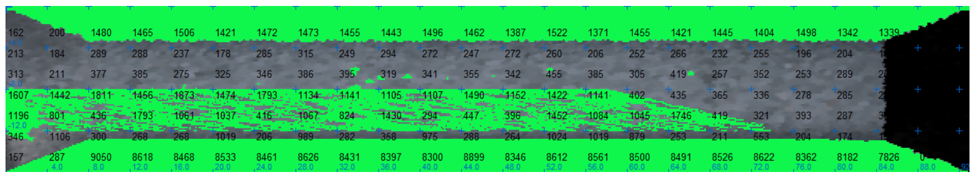
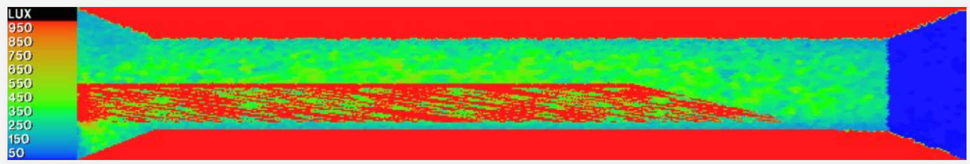
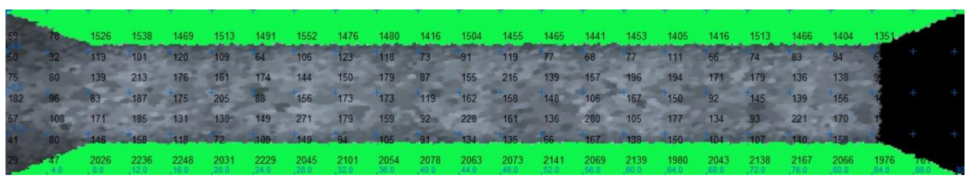
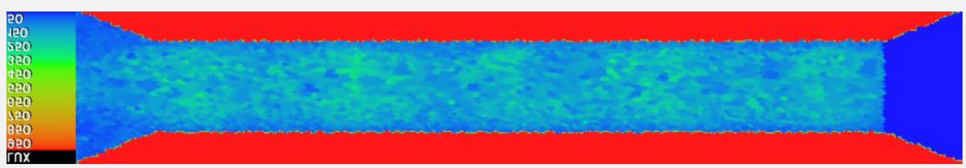
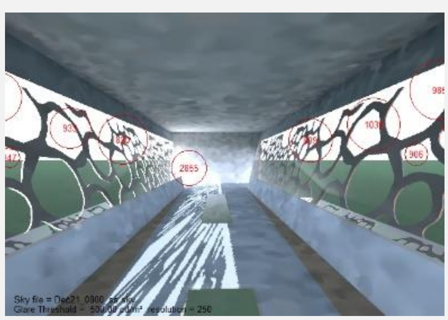
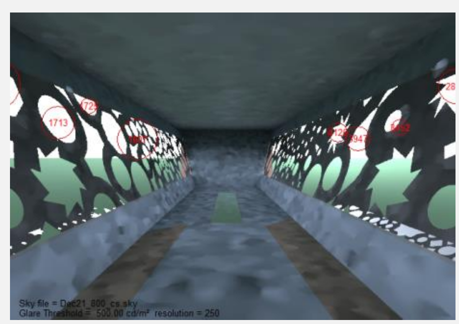
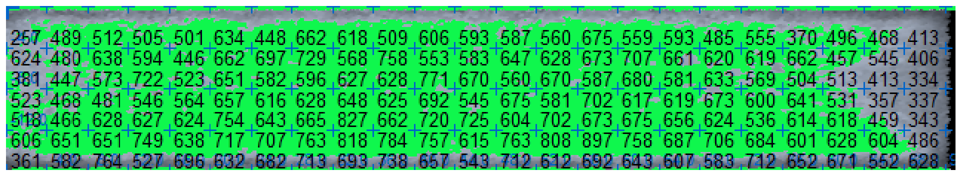
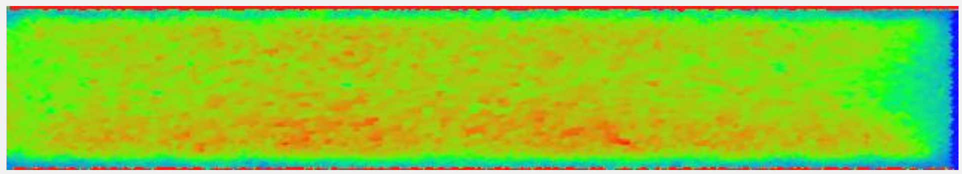
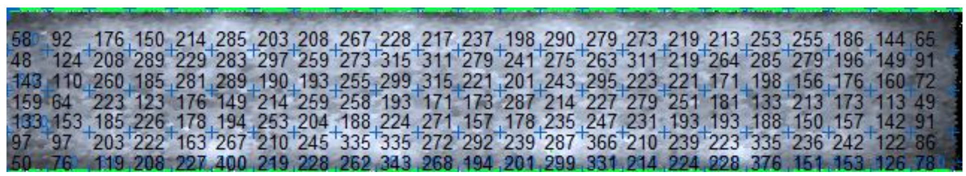
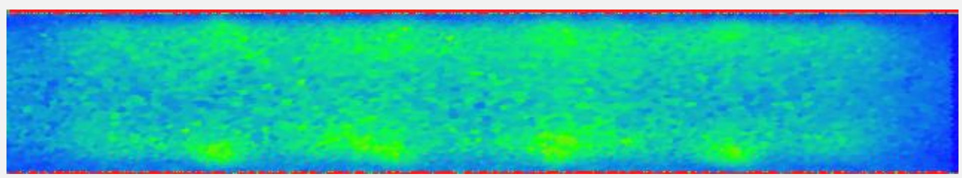
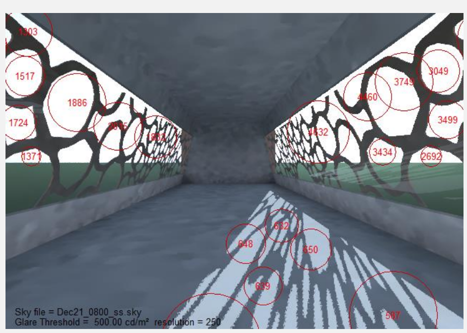
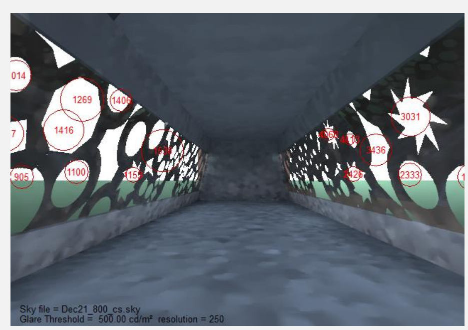
<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td></td><td></td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>2098.77 Lux</td><td>734.17 Lux</td></tr>
</table>

Table 61: SIM 7- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Mezzanine Floor

<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2">
</td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2">
</td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>596.48 Lux</td><td>257.72 Lux</td></tr>
</table>

In SIM 8, average illuminance levels are dropped from 1666.10 lux to 1501.71 lux in the Viewing Bridge as identified in Table 62. The reduction in the area of Illuminance levels above 500 lux are clearly illustrated in the optimal design illuminance plans. However, Table 63 present the enhancement in the average illuminance lux levels in the Mezzanine Floor where it is dropped from 1301.07 to 676.20 lux.

Table 62: SIM 8- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Viewing Bridge

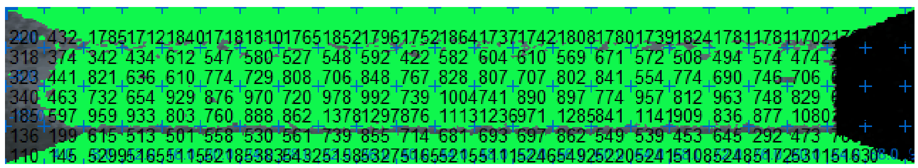
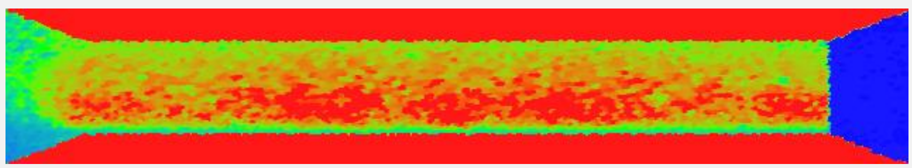
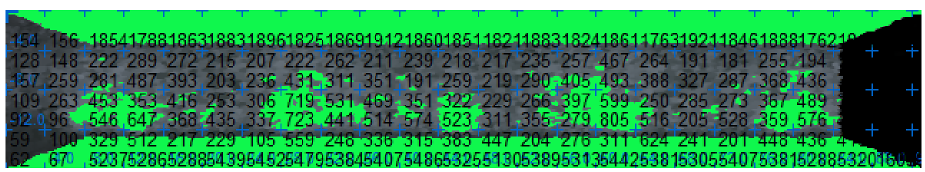
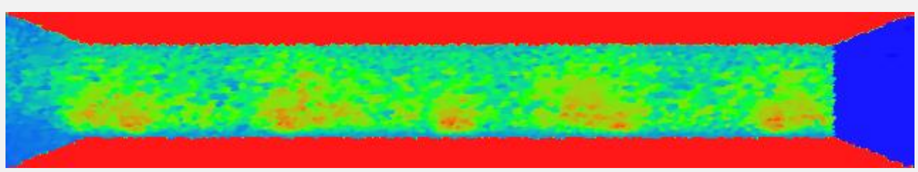
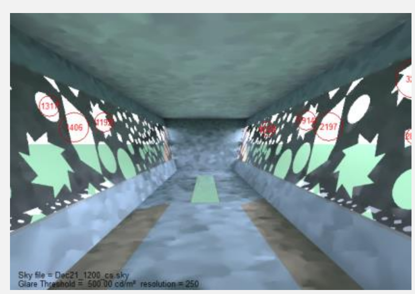
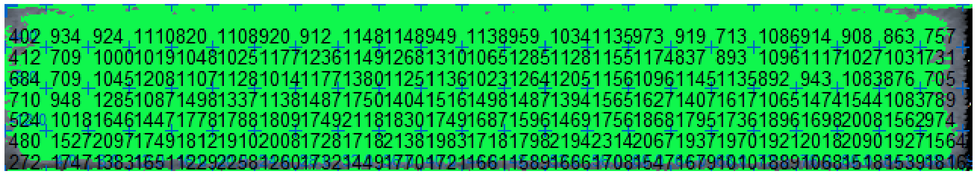
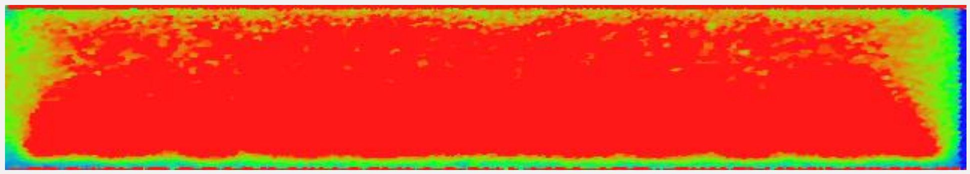
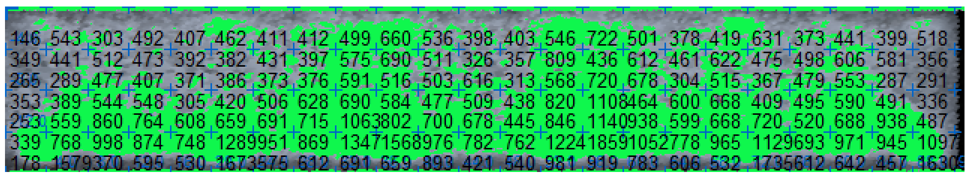
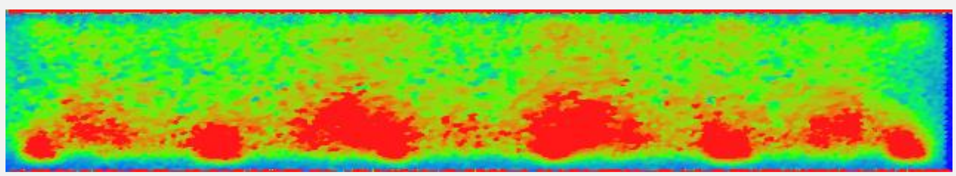
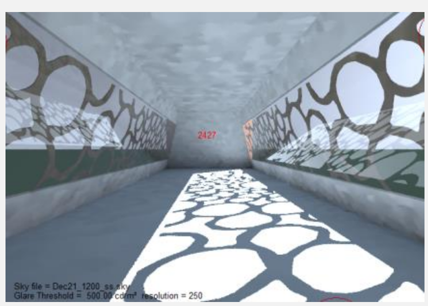
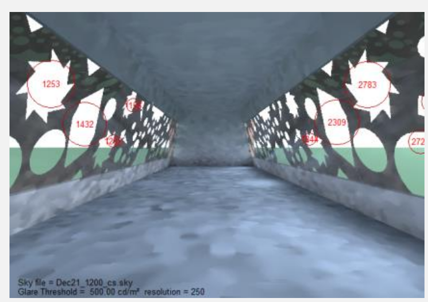
<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td></td><td></td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>1666.10 Lux</td><td>1501.71 Lux</td></tr>
</table>

Table 63: SIM 8- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Mezzanine Floor

Base case	Illuminance Plan		
	Radiance Contour Plan		
Optimal design	Illuminance Plan		
	Radiance Contour Plan		
Comparison		**Basecase**	**Optimal design**
Luminance Image (to show façade pattern and geometrics openings)			
AVE Illuminance levels (lux)		1301.07 Lux	676.20 Lux

In SIM 9, Table 64 shows a reduction the area of sun glare in the Viewing Bridge where illuminance levels are dropped from 692.30 to610.27 lux. On the other hand, in Table 65, illuminance levels are reduced from 552.48 to 211.70 in the Mezzanine Floor.

Table 64: SIM 9- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Viewing Bridge

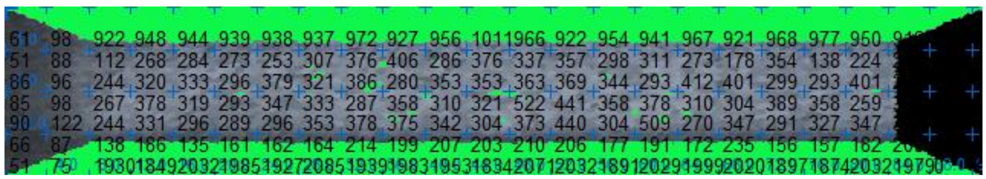
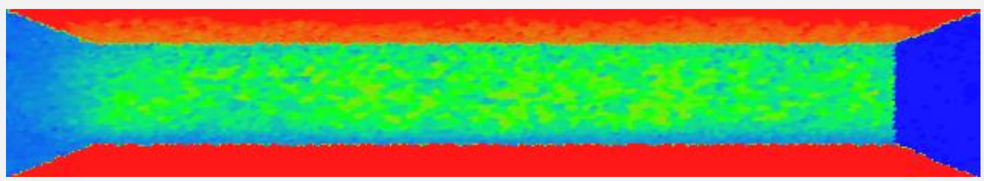
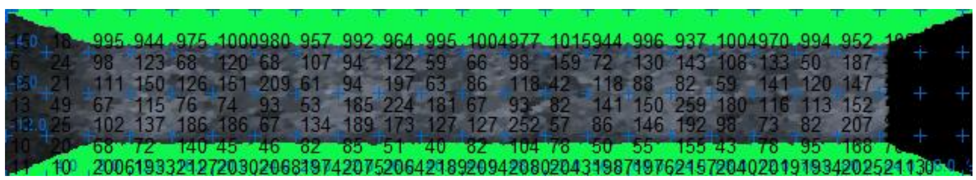
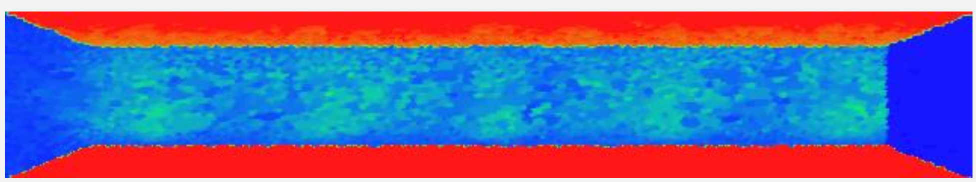
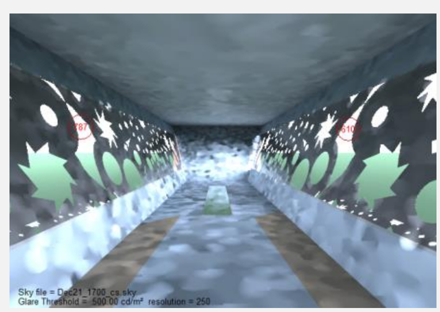
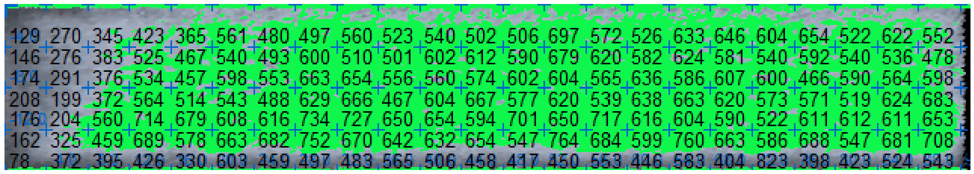
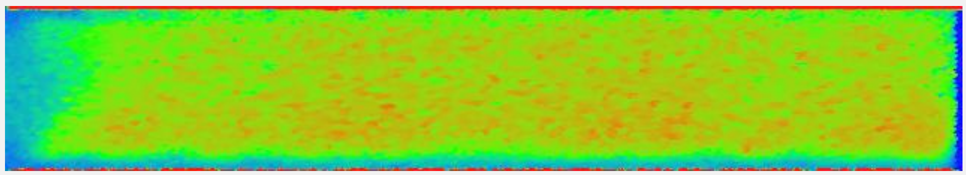
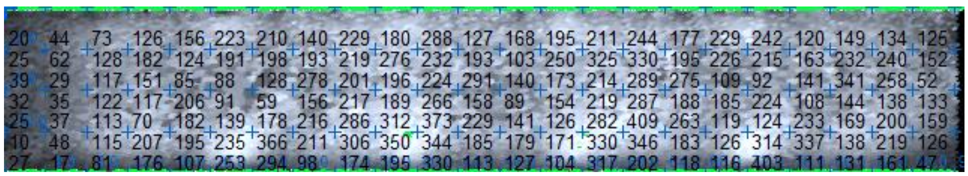
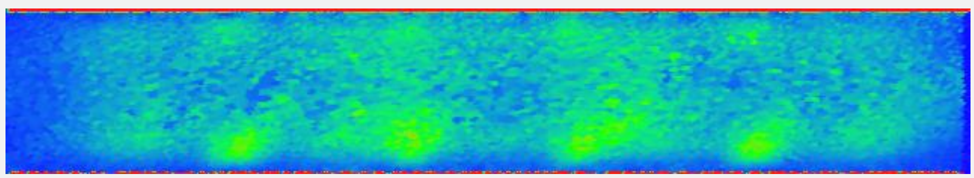
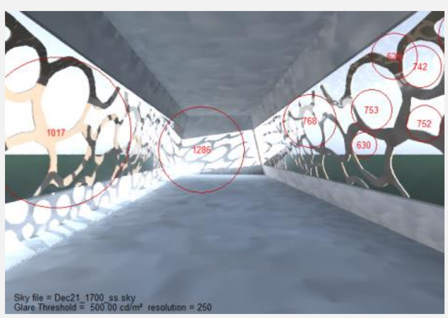
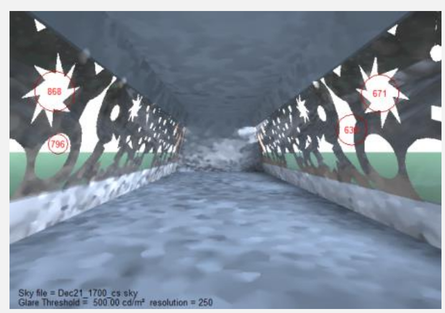
<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2"></td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td></td><td></td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>692.30 Lux</td><td>610.27 Lux</td></tr>
</table>

Table 65: SIM 9- Base Case vs. Optimal Design Illuminance and Radiance contour plans/ Mezzanine Floor

<table>
<tr><td rowspan="2">Base case</td><td>Illuminance Plan</td><td colspan="2">
</td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Optimal design</td><td>Illuminance Plan</td><td colspan="2">
</td></tr>
<tr><td>Radiance Contour Plan</td><td colspan="2"></td></tr>
<tr><td colspan="2">Comparison</td><td>Basecase</td><td>Optimal design</td></tr>
<tr><td colspan="2">Luminance Image
(to show façade pattern and geometrics openings)</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">AVE Illuminance levels (lux)</td><td>552.48 Lux</td><td>211.70 Lux</td></tr>
</table>

To summarize the impact of the proposed kinetic system on the selected case study daylighting measures, Figure 80 and Figure 81 show the areas of the base case that has undesired daylight illuminance levels in comparison to the optimal design in the Mezzanine Floor and the Viewing Bridge.

In the Mezzanine Floor, most of the proposed scenarios achieve a luminance level that range from 100-500 lux that is considered effective base on Daylight standards. However, in SIM 2 and SIM 5, illuminance levels are 824 and 1544.6 lux due to the South façade WWR which is resulted from the targeted overall energy savings of these scenarios. Nevertheless, the proposed kinetic behaviour managed to convert the space from uncomfortable in terms of visual and thermal aspects to a desirable and tolerable space based on daylight standards, ((Nabil & Mardaljevic 2006).

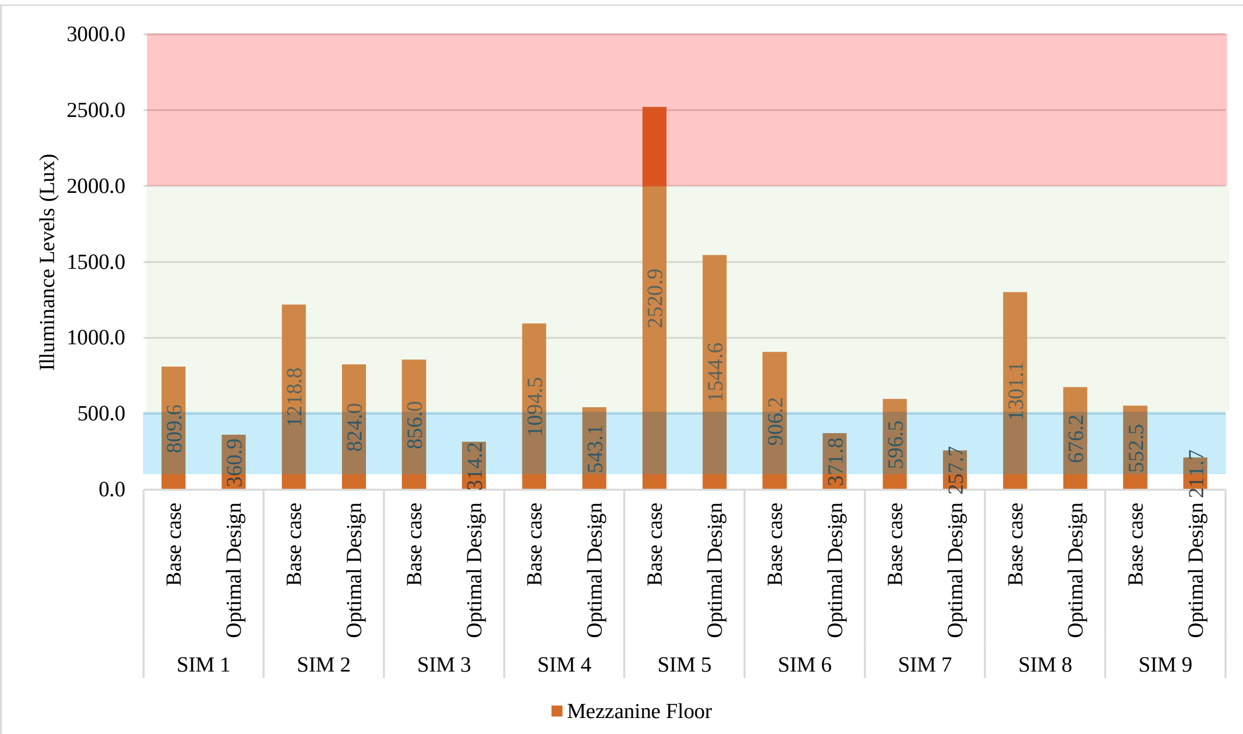


Figure 80: Base case and optimal design illuminance levels of SIM 1-9/ Mezzanine Floor

In the Viewing Bridge, the significant impact is found in the reduction of sun glare areas in both illuminance and radiance contour plans. However, in terms of illuminance levels, most of the scenarios kept the same range of lux levels from 500 to 2000 lux which is considered either as desirable or at least tolerable in reference to daylight standards.

On the other hand, SIM 7 reduced the base case illuminance levels from 2098 to 734.2 lux which makes the space desirable instead of uncomfortable in terms of thermal and visual aspects. Whereas SIM 05 is still in the discomfort zone but mostly close to the desirable range by reducing the base case illuminance levels from 3090.4 to 2527.9 lux.

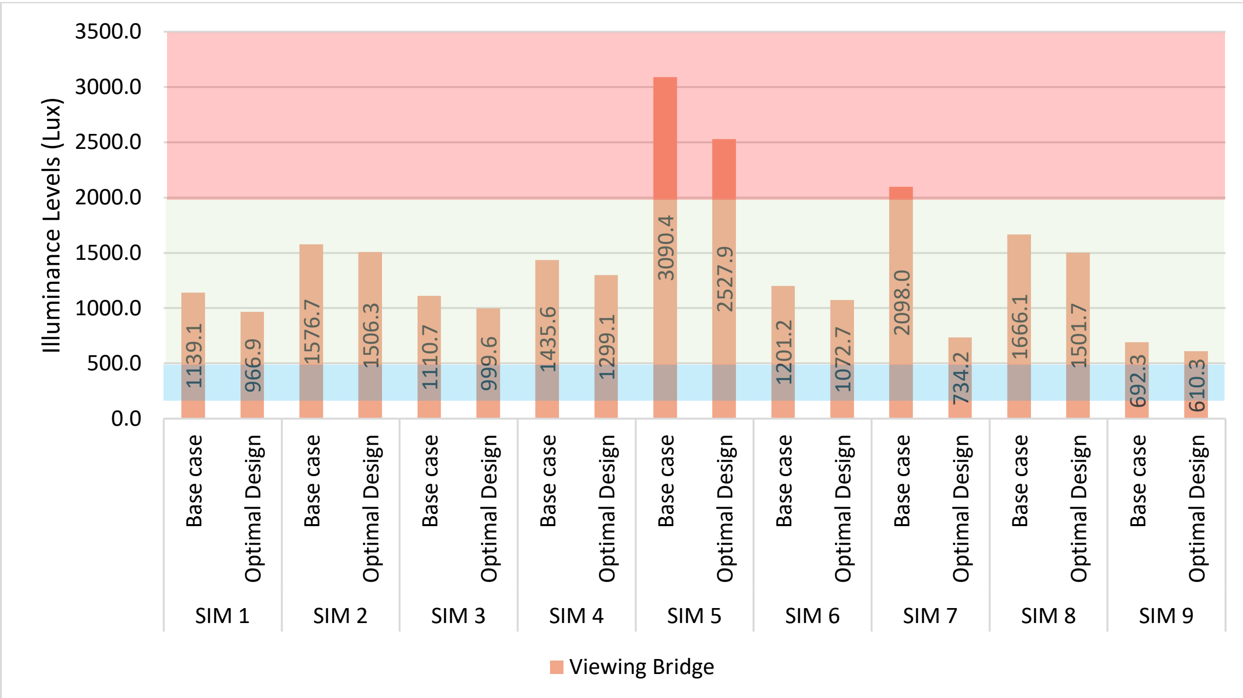


Figure 81: Base case and optimal design illuminance levels of SIM 1-9/ Viewing Bridge

Following the final daylighting results and the calculations presented in Figure 80 and Figure 81, a total reduction of illuminance levels is achieved by 31% as a result of proposing the kinetic system in the optimal design from SIM 1-9.

5.5 Linking the research results to the published Literature

Following the literature review summary and findings, an indication of the enhancement in kinetic façade systems in terms of cooling loads, energy consumption and daylighting performance will be illustrated in this section to be compared with the actual results generated from IES VE software for the proposed kinetic design of the selected case study.

Based on the literature cooling loads indicators, the average of kinetic façade reduction of heating and cooling would reach 30% as indicated by Alotaibi (2015). On the other hand, cooling loads is reduced by 9.8% in a South facing office in Athens, (Sega Sufia Purnama & Sutanto, 2018). Whereas, Elzeyadi (2017) mentioned that shading strategies enhancement for cooling and heating would range from 13.3% to 26.9%. In the proposed kinetic system, cooling loads were enhanced by 31% when it was based on the energy performance based-design strategy. However, after going through that cumulative process to adjust the WWR based on the sun exposure and the aesthetic values, the optimal design reduces cooling loads by 18%.

In addition, Wagdy et al. (2015) mentioned that a hybrid double façade contributes in 23% energy savings. However, Ahmed et al. (2016) stated that Kinetic Aluminium window frame would result in 18-20% of energy savings. Sharaidin & Salim (2012) added that 43% of energy savings can be achieved from kinetic shading. In the proposed kinetic system for the selected case study, an energy saving of 23% when it is achieved in SIM 1 to SIM 9. On the other hand, the annual reduction of energy savings equal to 16% with 249,901 Dhs cost savings.

Nevertheless, the proposed kinetic system results in a significant drop in daylighting illuminance levels that equals 31% and reduce the area of sun glare in both the Mezzanine Floor and the Viewing Bridge of the selected case study. However, the impact of the kinetic façade daylighting levels is not defined in the literature as most of the applications uses daylighting sensors that is set based on the comfort levels of the space to control the rotation, size and opening of kinetic geometrics, (Elghazi et al. 2014), (Nady, 2017), (Bacha & Bourbia, 2016).

CHAPTER SIX

CONCLUSION

Chapter 6 Conclusion

The chapter discusses the findings in view the outcome of objectives of this research and answer the research hypothesis both in terms of the impact of the proposed kinetic system on the building performance from the targeted energy savings and architectural perspective and the impact of WWR analysis on selecting the kinetic behaviour of the building.

In addition, it consists of the main contribution to the research in this field, research limitations related to the proposed kinetic strategies and research methodologies and propose further research areas entails of posing recommendations related to the topic.

The research hypothesises that were introduced at the beginning of this research are:

- ***Kinetic façade systems achieve the targeted energy savings that was resulted from previous case studies while maintaining the proposed architectural concepts and preserving the functionality of the building.*** The resulted energy savings from the proposed WWR analysis equal 31% as indicated in chapter 4, section 5 in the stage of selecting the kinetic scenarios. However, the optimal design that incorporate the architectural aspects of the building achieve an average of 23% reduction in SIM 1-9 as presented in chapter 5, section 1.
- ***The impact of WWR on the building energy performance levels can be used as a design strategy for selecting the kinetic behaviour of the building.*** This is confirmed in chapter 4, section 5; energy performance based-design strategy that presented the analysis of adjusting the façade WWR based on the targeted energy savings, which was used as a strategy for selecting the kinetic behaviour of the proposed geometrics through a parametric model using Grasshopper plugin.

On the other hand, the main objectives that were identified are:

- ***To understand the main parameters of kinetic design principles and help in creating efficient, applicable and creative adaptive systems.*** The key factors that affect the kinetic system performance are illustrated in chapter 2, section 7. Moreover, the main parameter that help in designing a kinetic system are presented in chapter 2 section 10.

- ***To provide a design strategy and methodological framework that response to three parameters; energy levels, cooling loads in reference to WWR analysis, sun exposure and the functionality of the building.*** Chapter 3, section 6, presents the methodological framework of this research.
- ***To introduce a new concept of shading systems by changing the façade traditional role to an active role in enhancing the energy performance of the building.*** Kinetic shading typologies and applications are presented in chapter 2 section 8 and 9. However, in chapter 4, section 5, a development of kinetic design strategies and processes are implemented to introduce a new concept of shading system for the selected case study.
- ***To modify the design through cumulative design process in reference to the main parameters of kinetic design principles.*** Chapter 4, section 4 and 5 present the strategies adopted in this research and the cumulative process used to select the kinetic scenarios of the proposed kinetic system.
- ***To propose an informative technology and kinetic architectural strategy at the same time.*** Chapter 4, section 5, stage four shows the development of a parametric model through Grasshopper to determine the configuration of the optimal WWR to achieve the targeted energy savings.
- ***To validate onsite measurements of energy consumption and daylighting levels using simulation software, IES VE, in this research to be accredited for Dubai Green Building evaluation system (Sa'fat).*** Chapter 4, section 3, shows the field measurements data and the analysis of energy bills that were used to validate the simulation results of IES VE software***.***
- ***To test the impact of the proposed kinetic system on indoor daylight levels to avoid sun glare and solar gain in the building.*** The impact of the kinetic system on daylighting levels is presented in Chapter 2, section 5, 8 and 10. Further, the impact of the proposed kinetic system is tested in chapter 5, section 3.
- ***To compare between proposed adaptive kinetic façade and base case fixed shading system in terms of cooling demand and energy consumption.*** Chapter 5, section 2, shows the comparison between the base case, the new abstract design and the optimal design from SIM1-9 in terms of total electricity and cooling loads.

- ***To generate a design that act as an integral part of the building and the surrounding context and identify different scenarios that can be applied during the year for further assessment.*** Chapter 5, section 2, shows how the selected scenarios are applied on three periods during the day then implemented on all months to generate an annual energy saving results of the proposed kinetic system.
- ***To investigate the enhancement of cost savings in terms of energy consumption for both electricity and cooling loads that can be achieved from kinetic system.*** Chapter 5, section 2, identifies the cost savings in reference to the annual cost of the total energy consumption for the base case and the optimal design.
- ***To achieve a highly efficient building that is more flexible to adapt to the external environment.*** This is the final outcome of all this research objectives that is confirmed in chapter 5.

6.1 Summary of the research

This research sets out on developing a kinetic system strategy selection framework focusing on environmental sustainability criteria and architectural aspects on an existing public building in Dubai; Dubai Frame. The main methodologies that were used to implement kinetic façade strategies to investigate the performance of kinetic systems consist of field experimental measurements, parametric tools using Grasshopper plugin and simulation tools using IES VE software.

In addition, the process of developing a kinetic system went through five stages to include in the first stage the main parameters considered in selecting the kinetic system by identifying the façade, pattern, movement, application, targeted energy savings and its architectural aspects in terms of the functionality of the building. In the second stage a selection of the kinetic typology in reference to the literature were used to redesign the façade in a more abstract pattern of geometrics to enable the kinetic mechanism that is investigated in third stage to be applied through scaling and material deformation.

After that, in stage four, three strategies were implemented to identify the kinetic behaviour of the façade in nine scenarios by illustrating the impact of each strategy on the geometrics opening and closing mechanism in reference to the total façade WWR. As a result of these strategies, stage 5 shows the cumulative process conducted to generate an optimal design from adjusting the proposed WWR in each scenario in respect to the targeted energy savings, thermal factors and aesthetic values.

Eventually, a simulation of the proposed kinetic system was conducted to investigate the performance of the proposed scenarios from SIM 1 to SIM 9 in comparison to the base case to test the total energy savings in terms of electricity and cooling loads and cost savings in terms of the KW per hour of electricity generated. In addition, daylighting illuminance levels were tested to avoid sun glare and uncomfortable thermal and visual spaces in reference to daylight standards.

6.2 Contributions of the research

The most important contribution of this research is the development of a kinetic system on an existing building to be able to conduct a comparison on real measurements in terms of daylighting levels and energy consumption that would be a reference for Dubai Municipality in the application of innovative systems. Moreover, this research proof that innovative technologies can go in parallel with the architectural aspects and still achieve the targeted energy savings, thermal performance and aesthetic values.

In addition, this research introduces the use of WWR as an energy performance based-design strategy for selecting the kinetic behaviour of the building. Further, this research proposes a parametric model for adjusting the opining ratios of the panel's solid parts in the façade geometrics. This can be achieved by developing four group of movement mechanisms that evaluates in moment the ratio between void area and the total area (WWR) which allows the researcher to capture the exact façade configuration in various movement scenarios.

Furthermore, the proposed kinetic system provides an energy saving of 23% for SIM 1 to SIM 9. However, when the scenarios are implemented on a period of time such as applying SIM 1 that was tested in March at 8:30 AM for the period from 8:30 to 10:30 AM, an average energy savings would reach up to 27% for March, June and December during 8:30 AM to 17:30 PM. On the other hand, when the proposed scenarios are applied seasonally and the data of the base case abstract is used for the time from 17:30 PM to 8:30 AM, an annual reduction of energy savings equal to 16% for electricity loads and 18% for cooling loads with 249,901 Dhs. cost savings.

Eventually, the proposed kinetic system results in a significant drop in daylighting illuminance levels that equals 31% and reduce the area of sun glare in both the Mezzanine Floor and the Viewing Bridge of the selected case study. However, the impact of the WWR are clearly shown in the daylighting results as SIM 2, SIM 5 and SIM 7, which have the highest South façade WWR, shows the least reduction in their daylight illuminance levels especially in the Viewing Bridge.

6.3 Research limitations

The main limitations of the research are listed as follows:

1. The results of the previous kinetic systems don't mention the energy required for the mechanical systems and doesn't represent the actual performance of the kinetic facade.
2. Available tools do not measure the energy embedded in the electronics, moving mechanics and computers required for controlling the kinetic behaviour of the façade.
3. IES VE software limitations
    a. Simulation tools are used to evaluate traditional design facades not kinetic systems. Therefore, to test a kinetic system, simulations are conducted for the peak loads, in this case, 21st of March, 21st of June and 21st of December.
    b. The software considers any rotated wall towards the ground as a floor and Sun cast analysis is not applicable on a floor.
    c. Importing the model from Sketch up, Revit and Grasshopper to IES VE did not work, as IES VE does not recognise curved geometrics. Therefore, the base case design, the base case abstract and the proposed 9 models were modelled in IES VE to enable the author to test the impact o the proposed scenarios.
    d. There is no option to test the WWR on a shading object configuration. Therefore, it was tested using pixelated windows of 2x2 m.
4. Field measurements limitations
    a. Site visit time was not conducted during the peak time of the year due to the research timeframe.
    b. Temperature measurements were not validated as the HVAC system operates for 24 hours and there was no access given when the building is closed for public.

c. The duration of conducting the measurements need one hour in order to go around the whole building. Therefore, due to the limited resources, it was hard to get all the measurements of the Mezzanine Floor and the Viewing Bridge at the exact time.
d. It took time to get a permission to do the field measurements for safety reasons as the building is considered one the iconic buildings and a touristic attraction in Dubai.

6.4 Future work

The future research should involve of evaluating and measuring the operation and the installation of the proposed kinetic system to test the energy loads of the façade embedded in control devices, computers and the mechanical systems. Further, structural loads calculation for the kinetic façade need to be compared with the existing shading system and used to propose fixation strategies for efficient application.

On the other hand, the previously discussed kinetic typologies in the literature can be also investigated to identify the optimal performance of these typologies and the parameters that would affect their kinetic behaviour, movement mechanism, energy performance, aesthetic performance and daylighting measures.

In addition, further assessment of kinetic systems parameters should be addressed in future studies such as the geometric depths required for the movement of the proposed kinetic surfaces that can be tested using laboratory small-scale prototypes.

Furthermore, additional studies of applying the proposed design strategies of kinetic systems can be tested on commercial buildings, different scales of buildings or even on an urban level. Moreover, multi simulation programs can be proposed as a simulation tool to be accredited and to validate the targeted performance of kinetic system that was applied in the research whether in UAE climate or even outside UAE in different climatic zones.

Eventually, the time required for installing the kinetic system and cost analysis of its materials and mechanical devices should be investigated at early design stage and on existing buildings to determine the payback period required for proposing this kind of innovative systems.

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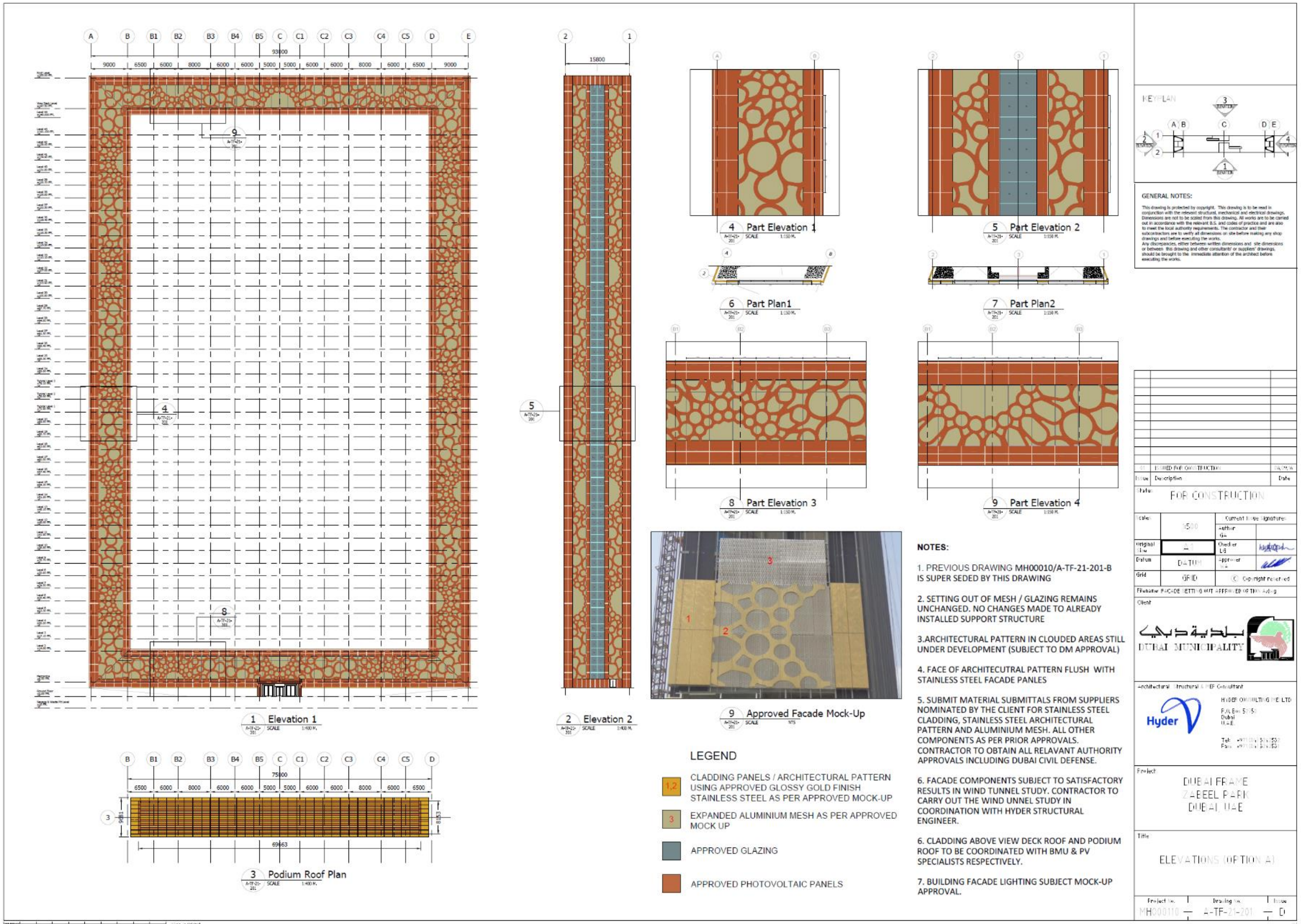
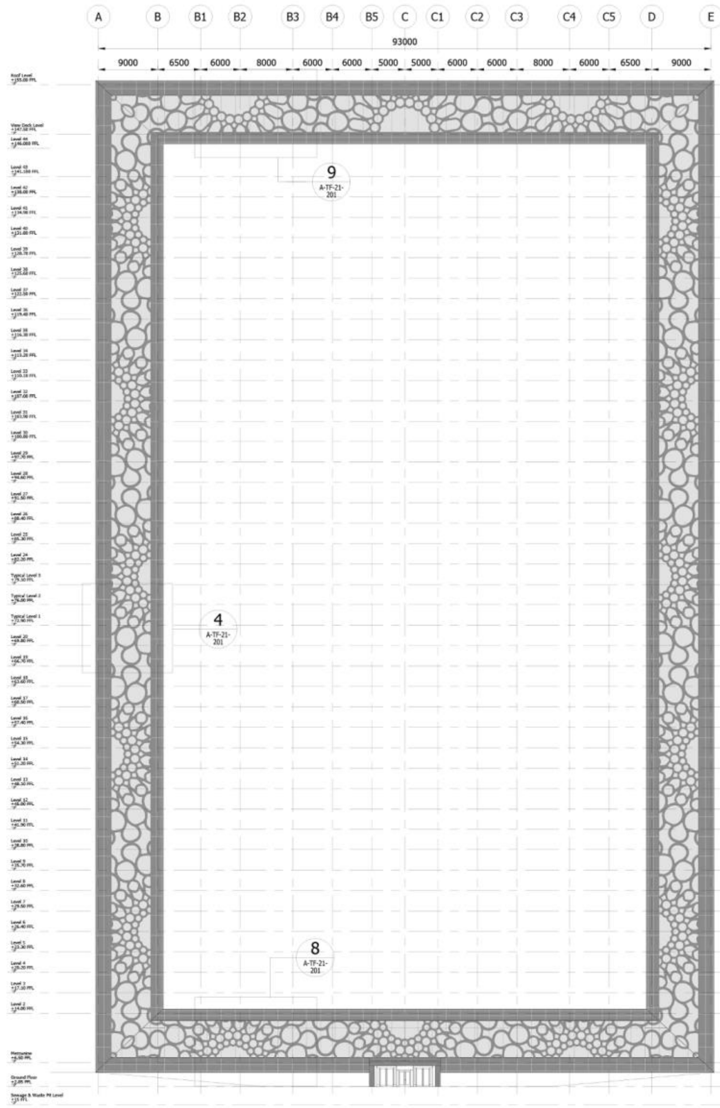
Appendix A


1 Elevation 1
2 Elevation 2
3 Podium Roof Plan
4 Part Elevation 1
5 Part Elevation 2
6 Part Plan1
7 Part Plan2
8 Part Elevation 3
9 Part Elevation 4
9 Approved Facade Mock-Up
LEGEND
CLADDING PANELS / ARCHITECTURAL PATTERN USING APPROVED GLOSSY GOLD FINISH STAINLESS STEEL AS PER APPROVED MOCK-UP
EXPANDED ALUMINIUM MESH AS PER APPROVED MOCK UP
APPROVED GLAZING
APPROVED PHOTOVOLTAIC PANELS
NOTES:
1. PREVIOUS DRAWING MH00010/A-TF-21-201-B IS SUPER SEDED BY THIS DRAWING
2. SETTING OUT OF MESH / GLAZING REMAINS UNCHANGED. NO CHANGES MADE TO ALREADY INSTALLED SUPPORT STRUCTURE
3.ARCHITECTURAL PATTERN IN CLOUDED AREAS STILL UNDER DEVELOPMENT (SUBJECT TO DM APPROVAL)
4. FACE OF ARCHITECUTRAL PATTERN FLUSH WITH STAINLESS STEEL FACADE PANLES
5. SUBMIT MATERIAL SUBMITTALS FROM SUPPLIERS NOMINATED BY THE CLIENT FOR STAINLESS STEEL CLADDING, STAINLESS STEEL ARCHITECTURAL PATTERN AND ALUMINIUM MESH. ALL OTHER COMPONENTS AS PER PRIOR APPROVALS. CONTRACTOR TO OBTAIN ALL RELAVANT AUTHORITY APPROVALS INCLUDING DUBAI CIVIL DEFENSE.
6. FACADE COMPONENTS SUBJECT TO SATISFACTORY RESULTS IN WIND TUNNEL STUDY. CONTRACTOR TO CARRY OUT THE WIND UNNEL STUDY IN COORDINATION WITH HYDER STRUCTURAL ENGINEER.
6. CLADDING ABOVE VIEW DECK ROOF AND PODIUM ROOF TO BE COORDINATED WITH BMU & PV SPECIALISTS RESPECTIVELY.
7. BUILDING FACADE LIGHTING SUBJECT MOCK-UP APPROVAL.
KEYPLAN
GENERAL NOTES:
FOR CONSTRUCTION
DUBAI MUNICIPALITY
Hyder
DUBAI FRAME
ZABEEL PARK
DUBAI UAE
ELEVATIONS (OPTION A)



1 Elevation 1
A-TF-21-
201
SCALE 1:400 M.