INVESTIGATING THE ENERGY PERFORMANCE OF DYNAMIC FACADES TOWARDS SUSTAINABLE OFFICE BUILDING IN HOT CLIMATES

BY

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DEDICATION

In loving memory of my father – Alhaji Adamu Garkuwa – who was second to none, to my precious mother, lovely wife, amiable daughter, step mothers, brothers, sisters, and friends, I dedicate this research to everyone who has patiently endured the pain of my absence during my stay in the Kingdom of Saudi Arabia Jazakumullahu Khairan.

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LIST OF ABBREVIATIONS

CO_2	:	Carbon dioxide
KSA	:	Kingdom of Saudi Arabia
BES	:	Building Energy Simulation
BIPV	:	Building Integrated Photovoltaics
BIST	:	Building Integrated Solar Thermal
TSTC	:	Transparent Solar Thermal Collectors
ObPV	:	Organic-based Photovoltaics
DSC	:	Dye-sensitized Cells
EU	:	European Union
SEC	:	Saudi Electricity Company
nZEB	:	near Zero Energy Buildings
IEQ	:	Indoor Environmental Quality
ECM	:	Energy Conservation Measure
WWR	:	Window-to-Wall Ratio
HVAC	:	Heating Ventilation and Air Conditioning
MWh	:	Mega Watt hour
CABS	:	Climate Adaptive Building Shell
kWh	:	Kilo Watt hour
TSTC	:	Transparent Solar Thermal Collectors
AHVT	:	Air Heating Vacuum Tube
MVF	:	Mechanically Ventilated Façade
STBIPV	:	Semi-Transparent Building-Integrated Photovoltaic
STBIPV/T	:	Semi-Transparent Building-Integrated Photovoltaic Thermal
EIFS	:	Exterior Insulation and Finish System
ETFE	:	Ethylene tetrafluoroethylene

ICT	:	Information and Communication Technology
GFRP	:	Glass Fiber Reinforced Polymer
UAP	:	Urban Art Projects
ANN	:	Artificial Neural Network
CA	:	Cellular Automata
GA	:	Genetic Algorithms
GPS	:	Global Positioning System
ICD	:	Institute of Computational Design
EAP	:	ElectroActive Polymers
MFM	:	Multifunctional Façade Module
PFSS	:	Polarized Film Shading System
CASS	:	Cellular Automaton Shading System
BSP	:	Building Simulation Programs
RBE	:	Responsive Building Element
GUI	:	Graphical User Interface
ASHRAE	:	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CIBSE	:	Chartered Institution of Building Services Engineers
LEED	:	Leadership in Energy and Environmental Design
BIM	:	Building Information Modeling
CFD	:	Computational Fluid Dynamics
PSZ	:	Packaged Single Zone
FCU	:	Fan Coil Unit
LPD	:	Lighting Power Density
EAT	:	Energy Analysis Tools
VAV	:	Variable Air Volume
PVC	:	Polyvinylchloride
TCE	:	Total Cooling Energy

SGEW	:	Solar Gains Exterior Windows
LEC	:	Lighting Energy Consumption
ZSC	:	Zone Sensible Cooling
TEC	:	Total Energy Consumption
DF	:	Dynamic Façade
SS	:	Solid Screen
SW	:	South-West
PMV	:	Predicted Mean Vote
TCL	:	Total Cooling Load

ABSTRACT

Full Name : JAMILU ADAMU GARKUWA

Thesis Title : INVESTIGTING THE ENERGY PERFORMANCE OF DYNAMIC FACADES TOWARDS SUSTAINABLE OFFICE BUILDING IN HOT CLIMATES

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Global energy and climate crises necessitate new ideas and investments to develop energy-efficient strategies in the building industry. The building sector is responsible for over 40% of total primary energy consumption across the globe and nearly up to 30% of the world's total Carbon Dioxide (CO_2) emissions and therefore plays a critical role in addressing global energy and climate change issues. As a representative of hot climates for example, air conditioning systems in buildings across the Kingdom of Saudi Arabia (KSA) account for nearly 70% of total energy consumed in buildings compared to only 22% and 21% the United Kingdom and the United States respectively. The building envelope design is a key element in the management of energy conservation practices in buildings. In contrast to conventional static building envelopes, the development of innovative dynamic facades is emerging as ideal envelope systems characterized by the capability of continuously changing some of their thermo-physical and optical properties. This study explores the concept of dynamic façade in the context of historical background. It discusses the various types of dynamic facades, classifies the technologies involved and their respective characteristics, and describes their design and details. The research investigates the energy performance of dynamic facades to develop guidelines to help designers with important considerations regarding dynamic façade usage. Although there were some identified limitations, nevertheless dynamic facade achieved maximum annual total cooling energy savings of 35.5% and 18.5% compared to a performing theoretical and real base cases respectively. This emphasizes the energy efficiency of dynamic façades and how important they can be in energy-efficient building envelope designs. The research concludes with a set of recommendations to help improve the modeling, configuration, and simulation of dynamic facades in *DesignBuilder* and other Building Energy Simulation (BES) tools.

ملخص الرسالة

الاسم الكامل: جميلو آدمو جاركوا

عنوان الرسالة: التحقق من أداء الطاقة للواجهات الديناميكية نحو مباني إدارية مستدامة في المناطق ذات المناخ الحار

التخصص: الهندسة المعمارية

تاريخ الدرجة العلمية: مايو 2017

هيأت أزمة الطاقة والمناخ العالمية لأفكار واستثمارات جديدة لتطويراستراتيجيات ترشيد الطاقة في قطاع المباني. فالمباني وحدها مسؤولة عن أكثر من 40% من إجمالي استهلاك الطاقة الأساسي في العالم كما أنها مصدر لحوالي 30% من انبعاثات غاز ثاني أكسيد الكربون، ولذلك فهي تلعب دور مهم في قضايا الطاقة والمناخ. على سبيل المثال في المناطق ذات المناخ الحار تستهلك أجهزة تكييف الهواء في المملكة العربية السعودية ما يعادل 70% من اجمالي الطاقة المستخدمة في المباني، بالمقابل، فإن كلا من المملكة المتحدة والولايات المتحدة الأمريكية يستهلكان ما يقارب من 22% و21% على الترتيب. ويعتبر تصميم غلاف المبنى العنصر الأساسي في إستراتيجيات ترشيد الطاقة في المباني. على النقيض من تصاميم الواجهات الثابتة التقليدية، فإن تطوير واجهات ديناميكية مبتكرة تعتبر فكرة مستجدة كنظام يتمثل بالقدرة على التغيير المستمر في خصائص المبنى الحرارية-الفيزيائية والبصرية. تتعرض هذه الدراسة لتاريخ تطورالواجهات الديناميكية، كما تناقش نماذجها المتنوعة، و تصنف الدراسة التكنولوجيات المساهمة في تطوير و خصائص الواجهات الديناميكية. علاوة على ذلك، فإن هذه الدراسة تبحث عن الأطر التنظيمية لأداء الطاقة للواجهات الديناميكية لإمداد المصممين بالاعتبارات الهامة والتي تخص استخداماتها. و طبقا للنتائج حقق استخدام الواجهات الديناميكية ارشادا للطاقة بما يعادل %35.5 ومقارنة %18.5 في حالات نظرية و حقيقية. هذا يوضح مدى أهمية الواجهات الديناميكية كعناصر ذات كفاءة للطاقة ويؤكد دورها الفعال في تصميم غلاف المباني و انعكاس ذلك على كفاءة استخدام الطاقة فيها. وتضمن البحث العديد من التوصيات للمساعدة في تطوير نمذجة ومحاكاة الواجهات الديناميكية باستخدام برنامج (DesignBuilder) أو أي برنامج آخر يستخدم لمحاكاة الطاقة في المباني.

CHAPTER 1

INTRODUCTION

1.1 Background

Global energy and climate crises necessitate new ideas and investments in energy efficient strategies in the building industry **[1]**. The building sector consumes over 40% of overall primary energy consumption across the globe **[2]**. Also the building sector is responsible for almost up to 30% of the world's overall Carbon Dioxide (CO2) emissions and therefore plays a critical role in addressing global energy and climate issues **[2]**. In an attempt to satisfy certain performance requirements, the concept of systems integration and dynamic façade is continuously used in facade design **[3]**. As such, new ideas and innovation related to the building façade such as Building Integrated Photovoltaics (BIPV), Building Integrated Solar Thermal (BIST), Transparent Solar Thermal Collectors (TSTC), Organic-based Photovoltaics (ObPV), Electrochromic glasses, and Dye-sensitized Cells (DSC) were introduced among other numerous technologies. Buildings account for 40% of total energy consumption and 35% of the total carbon dioxide (CO_2) emitted in the European Union (EU) regions. As such, in its effort to protect the environment and reduce energy consumption in buildings, the EU encourages member countries to increase the number of "nearly zero-energy buildings" **[4]**. In regions across hot-humid climates for instance, Kingdom of Saudi Arabia (KSA) as a representative is not an exception. In 2012, KSA was the world's largest oil producer and second largest owner of crude oil reserves and is naturally endowed with fossil fuel resources. Subsidy of this resources lead to misuse of energy and increase high level of CO_2 emissions **[5]**. F. Alrashed and M. Asif (2015) indicated that residential sector alone account for 52% of the national electricity consumed in Saudi Arabia **[6]**. Figure 1.1 shows the flow of electricity across Saudi Arabia for each sector as provided by Saudi Electricity Company (SEC) annual report for the year 2014 [7].

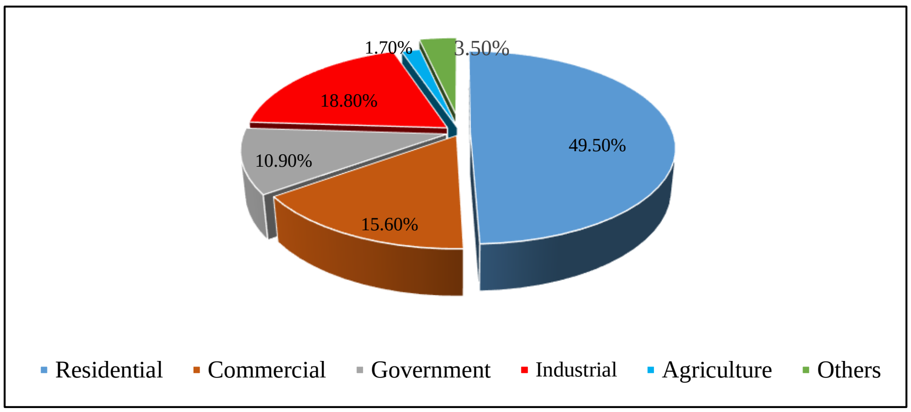


Figure 1.1 Electricity flow in the KSA [7].

Based on analysis conducted by Saudi Electricity Company, N. Ashraf and F. Al-Maziad concluded that, in KSA, buildings' air conditioning systems account for nearly 70% of total energy consumed in buildings. On the other hand, only 22% and 21% of total energy consumption in buildings is consumed by air conditioning in the United Kingdom and the United States respectively [8]. Figure 1.2 indicates electricity consumed by air conditioning and other systems in KSA **[9]**.

1.2 Problem Statement

The building industry plays a significant role in environmental degradation leading to greenhouse gas emission. As such, new strict rules aimed at minimizing total energy utilization in buildings are constantly established. For that reason, new concepts and technologies must be developed to enhance energy efficiency of the buildings to almost Zero Energy Buildings (nZEB) according to the European context. The building envelope is a key element in the management of energy conservation within buildings as well as in the utilization of renewable energy in buildings. The design and configuration of the building facade determines the magnitude in the reduction of total energy demand within building **[10]**.

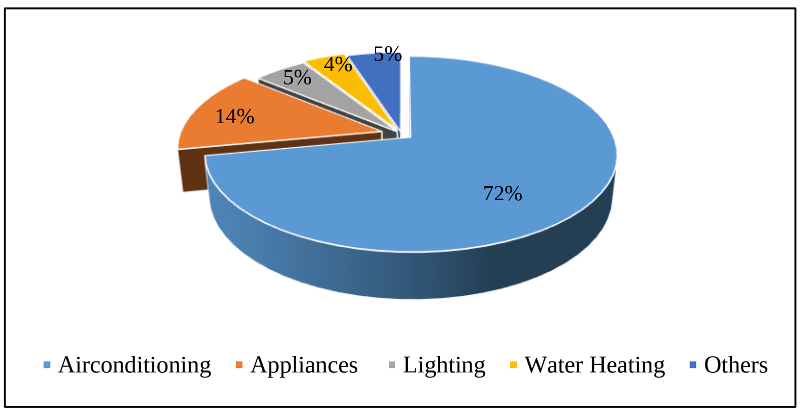


Figure 1.2 Residential power demand [9].

Francesco Goia et. Al [10] define dynamic building as “an ideal building envelope system characterized by the capability of continuously changing (within a certain range) some of its thermo-physical and optical properties”. This continuous change in appearance is aimed at controlling the energy demands of buildings which simultaneously enhances their aesthetical appearance from the outside.

1.3 Objectives of the Study

The study objectives are itemized below:

- To identify the characteristics of dynamic building facades' types, details and technology suitable for hot climates.
- To investigate the energy performance of dynamic facades in conserving energy while maintaining thermal and visual comfort in buildings.
- To develop guidelines for modelling and examining the energy performance of a building dynamic façade.

1.4 Significance of the Research

The proposed work is in line with the current global trend of sustainable design which maximizes daylight in buildings and reduces energy consumption while achieving thermal comfort at the same time. Subsequently, KSA as a representative of hot-humid climate, the research aligned itself with the recent initiatives by the Saudi government to reduce energy consumption in buildings (SEC, 2014). The research work also will equally create more awareness to the public and promote sustainable practices in the building sector. Again, it shall add to the body of knowledge thereby benefitting teaching and subsequent research in the future.

1.5 Scope and Limitation of the Research

The research is limited to maximizing thermal comfort, visual comfort as well as reduce energy consumption in office buildings as three (3) components of sustainability. Therefore other components of sustainability other than these three will not be addressed. Also, economic aspects regarding life-cycle costing will not form part of this research. In the event where the weather data file of Dhahran is not available in the selected software tool, the building will be simulated under the hot-humid climatic conditions of Riyadh, KSA. All findings and analysis of this research shall be limited to the selected office building which consist of 9 floors (storeys) and a mezzanine as a base case.

1.6 Research Methodology

An integral part of the research methodology is to develop an approach to model a dynamic façade utilizing the available energy simulation tools. In order to achieve the objectives of the research, the methodology is categorized in to five (5) main phases as described below:

1.6.1 Phase 1: Review of Related Literature

- Clearly define the concept of dynamic façade and obtain required information from built case studies regarding its usage.
- Obtain relevant information regarding various components, materials and technology involved.

- Identify various types of dynamic facades and their respective characteristics such as: energy saving potential, occupant comfort, area of application, advantages and disadvantages, aesthetical appearance, maintainability.
- Get acquainted with technology involved with dynamic facades.
- Develop a matrix for selection of dynamic façade types.

1.6.2 Phase 2: Building Selection and Audit

In 2010, Mohammed Abdul Najid [11] examined the operation of an office HVAC system situated in the eastern province of KSA, Dhahran (Al-Khobar to be specific). The building is a representative of offices across the hot-humid climatic regions. The building is chosen as a case study due to its practicability and provides the required information needed for modelling and simulation. The author collected building data after thumbing through the building's architectural, mechanical and electrical drawings as well as weather data and utility bills. Other methods of data collection carried out by the author involve conducting measurements, walkthrough evaluation survey, and issuance of questionnaire survey to the building occupants to assess the thermal comfort.

1.6.3 Phase 3: Formulation of Base Case Model and Simulation

- The utilization of powerful software for modelling, simulation and analysis (Design Builder 4.7) to model the selected office building as base case.
- Examine and compare the energy performance of alternative dynamic façade configurations in terms of performance compared to that of a conventional façade of the same properties from a life cycle perspective.
- Run simulations accordingly and examine the impact on energy consumption.

1.6.4 Phase 4: Discussion of Results and Analysis

- Detail energy analysis shall be made to compare between energy efficient dynamic facades against a conventional (static) façade.

1.6.5 Phase 5: Conclusion and Recommendations

- Conclusion based on the outcome of the research work and the anticipated future work shall be stated. Figure 1.3 illustrates the schematic summary of the research methodology.

1.7 Research Outcome

The intended outcomes of this research work will constitute the following:

- A comprehensive and comparative analysis of dynamic building facades alternative solutions with detailed information on their types, concept, technology and details.

- A model of sustainable office building with dynamic façade which optimize daylight utilization, enhances thermal comfort and reduce energy demand.

- To come up with various guidelines to the endless challenges of modelling a dynamic façade.

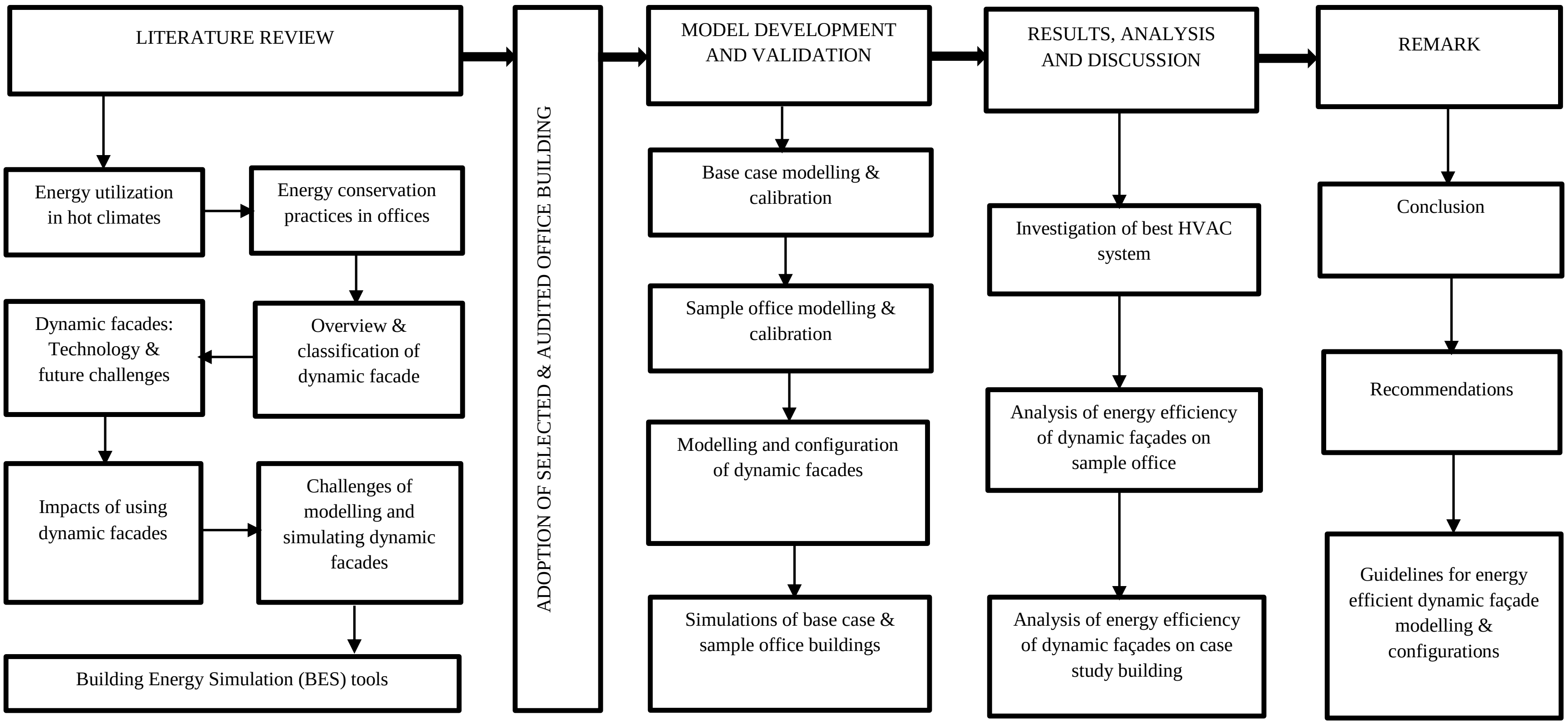


Figure 1.3 Schematic summary of the research methodology

CHAPTER 2

LITERATURE REVIEW

This chapter provides a review of previous and ongoing research work conducted by different researchers on this aspect. The knowledge gained through this review was found crucial during the course of this work. Key observations from the reviewed studies are summarized at the end of this chapter.

2.1 Energy Utilization in Hot Climates (KSA as a Case Study)

Hot-humid climate regions of the world often depend on fossil fuel for generation of electricity. For instance, Al-Rubaih, M. S. [12] described Saudi Arabia as a country which majorly depends on fossil fuel for generation of electricity. Electric energy forms the backbone of energy delivered to buildings. A country characterized by hot climatic conditions, the temperature could go as high as 55^0C in certain areas. All year round, the coastal regions remain hot and humid. As such, people depend solely on controlled indoor conditions for their comfort [12]. Thus, a significant percentage of energy is consumed in buildings to provide acceptable levels of comfort. In its annual report, SEC disclosed that between 2013 and 2014 alone, a growth of 8% was realised in total peak loads (SEC, 2014) [13]. As Figure 1.1 indicated, a greater percentage of the energy utilized in KSA is used in buildings. The building sector, which consists of residential and commercial buildings consume 50% and 15% respectively. An aggregate that accounts for 65% of the overall electricity produced in KSA [7].

As part of a conference proceedings, Al-Arfag K. A [14] indicated that most of the energy used in buildings across Saudi Arabia is consumed by HVAC systems in an attempt to provide optimum thermal comfort to building occupants [14]. In another research, Al Rabghi et al. [15] reported that, in coastal cities such as Jeddah, HVAC systems consumed approximately 60% of entire energy utilized in buildings during summer in order to achieve internal comfort [15]. Therefore, sustainable strategies that will enhance thermal and visual comforts, and reduce the amount of energy consumed in buildings will be of enormous benefits across KSA in particular, and to the entire hot-humid climatic regions.

2.2 Energy Conservation Practices in Office Buildings: Case Studies

Belal A. and Nader C. [16] studied how office buildings' total energy consumption peak demands are directly affected by design variables applied to their facades. The authors conclude by emphasizing the importance of achieving proper balance between shading and daylight for optimum energy utilization in office buildings [16].

Another concept of energy savings in office buildings especially in hot climate is bio-inspired adaptive building shells or breathing facades [17-18]. Elghawaby M. [17] developed a conceptual biomimetic model of 'breathing wall' and tested via comparison with a solid wall model. Obtained results indicated that breathing walls have better thermal behavior as against traditional solid wall [17]. Bio-inspired adaptive building skins are capable of enhancing energy efficiency and improve Indoor Environmental Quality (IEQ) [18].

In another study, Nurdil et al. investigated several energy conservation measures (ECMs) for office buildings in four different climatic conditions of Turkey. Simulation results indicated that yearly cooling energy as well as overall energy demands of office buildings with large window-to-wall ratio (WWR) increases significantly compared to buildings with lower WWR [19]. Therefore, it is highly recommended to optimize envelope design to reduce energy consumption in such buildings.

In an attempt to develop a cost-effective HVAC control strategies that guarantees adequate indoor thermal comfort and optimal energy utilization, Mathews et al. conducted a case study that investigated different retrofit techniques. Reset and setback control, improved HVAC system start–stop times together with air-bypass was found to be more profitable with a yearly estimated energy savings of 66% (1900 MWh) with an estimated simple payback period of 9 months. An energy saving that translates to 30% reduction of the building's overall energy consumption [20].

Pan et al [21] conducted a study in a mixed-use building involving offices and hotels. During the course of the study, energy savings of three possible HVAC related ECMs were determined through calculation. Energy Conservation Measure-1 (ECM-1) which involves changing both the secondary chilled water pumps and hot water pumps from constant to variable speed was found to be the best as it saves 5% of annual electricity energy used. On the contrary, ECM-2 which involves *free cooling* does not save appreciable energy due to high outdoor relative humidity of the study area [21].

2.3 Overview and Classification of Dynamic Facades

The concept of dynamic façade has been studied by various authors. As such, numerous names or variations have been designated for the concept. Some of which include: dynamic [22], adaptive [22, 27], responsive [32], automated [28], innovative [25] CABS [26, 27, 22] etc. Loonen R.C.G.M. [22] stated that even though these expressions may somewhat have different meanings, they are often used interchangeably to refer to dynamic façade [22]. However, CABS seem to be more used by researchers to refer to the concept of dynamic façade. According to Loonen R.C.G.M. et al. [22] "a climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance" [22].

Climate Adaptive Building Shells is a phenomenon that has been studied by different researchers and viewed as an important step towards the realization of the nZEB target or even energy producing buildings. In all instances, the concept of advanced responsive multi-functional façade as it is often referred to be is viewed as a technology where buildings' energy consumption can be optimized, through: maximizing daylight; control of indoor thermal gains; improvement of visual comfort; and maintaining good indoor air quality within buildings [22-29].

In a study conducted by Francesco Goia et al. [23] in an attempt to assess the impacts of dynamic (kinetic) façade over static façades, the authors perceived the basic idea behind an optimal building envelope system is distinguished by its ability to intuitively and continuously change some of its thermo-optical and physical properties in order to minimize the total energy demand of the building [23].

Baldinelli G. [24] used the climatic data of central Italy to conduct a research aimed at optimizing the energy performance of both winter and summer. Three different modelling levels employed were: optics of materials, fluid dynamics of the double skin façade and building energy balance. Interestingly, when compared with traditional enclosures such as glazed and opaque walls in an office room in the same location, the façade performance showed improved energy behaviour all year round. Compared to an opaque wall, an energy saving of up to 60 kWh per year per façade square meter was realized. Although the energy savings weakened when compared to a glazed wall, indoor comfort improves significantly [24]. Figure 2.1 shows the prototype of the double skin façade proposed in an open configuration [24].

In an attempt to establish an optimal range of adaptive thermo-optical performance of a glazed façade, based on the time scale of the adaptive mechanisms, Fabio F. et al. [25] conducted a study which revealed that the time scale of the adaptive façade mechanism is proportionate to the energy saving potential of the glazed façade [25]. Loonen R.C.G.M. et al. [26] studied how simulation provides insights into obstacle solving related to integration of innovative building façade components at an early stage. The results of the experiment prove vital in testing alternative solutions to determine options with higher chances of success [26]. In an earlier research, Loonen R.C.G.M et al. [27] explored the potentials of CABS by using building performance simulation combined with multi-objective optimization and advanced control strategies. Results obtained indicated that the application of CABS improves building performance far beyond the level of the best static building shell design [27].

Figure 2.1 Prototype of the double skin façade proposed in an open configuration [24].

Based on the order of multi-objective optimization scenarios, Kacinalis C. et al. [28] developed a framework for the design and analysis of CABS performance with optimum seasonal adaptation strategies. The framework uses a genetic algorithm combined with coupled building energy and day lighting simulations. The framework was applied on case study of an office building in Netherlands. Results indicated that monthly adaptation of six façade design lead to energy savings of 15-18% and improved IEQ conditions compared to a performing static building shell [28]. Figure 2.2 shows a schematic overview of the investigated office zone model. The position of the work plane (grey circle) is located in the south-oriented half of the zone [28].

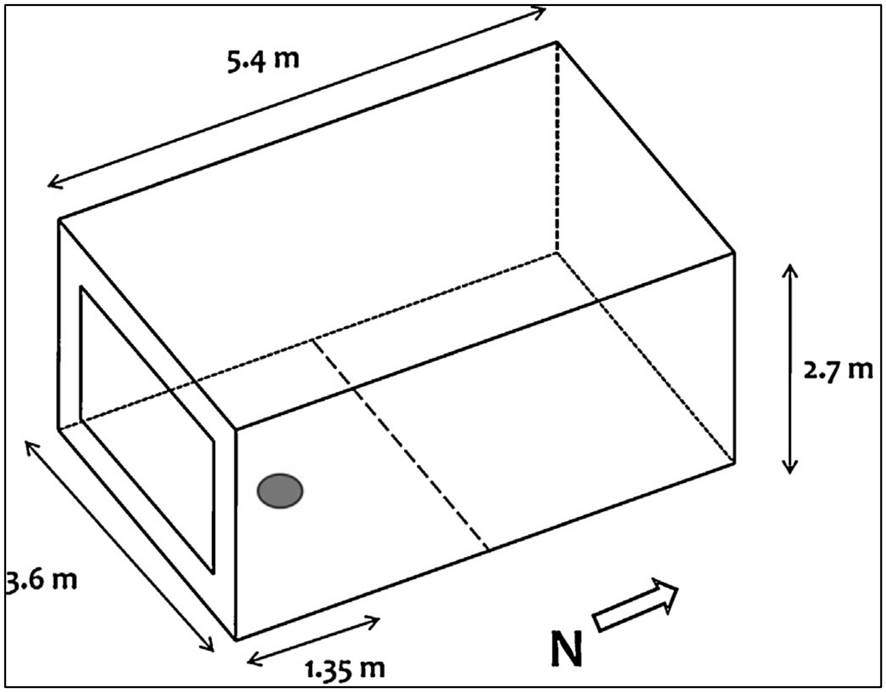


Figure 2.2 A schematic overview of the investigated office zone model [28].

Interestingly, L.G. Bakker et al. [29] conducted a study that explores and quantifies the influence of dynamic facade operation on user satisfaction and interaction. The pilot study was conducted by experimenting 26 participants using multiple scenarios with varying control strategies. The findings of the study revealed that dynamic façade does not directly present a high risk for disturbance and discomfort. Also, occupants suggested that there should be manual or control of the movement of the shells (skins). And finally, less frequent and detached façade configurations were chosen to be better than high frequency, smooth transition facades [29].

Basically, dynamic facades have been classified from two perspectives. Firstly, they are classified based on their dynamism when it comes to movement. Alternatively, they are classified based on their ability to allow or restrict daylight from reaching the interior of buildings.

2.3.1 Classification Based on Nature of Movement

This classification uses either *movement* or *structure* as the conceptual framework. 'Movement' definitions have to do with terms like *rotation* and *translation* to articulate the morphological output. Whilst 'Structural' definition uses terms such as *telescopic*, *scissor* and *folding plates* among others to describe how the morphological transformation is achieved [30].

2.3.2 Classification Based on Light Penetration Ability

This classification is from a building design and engineering perspective and it is more commonly used [31]. According to Chi-Ming Lai and Hokoi S. [31] building facade can be divided into two parts: solid and void. In other literature, *solid* is represented as '*opaque*' while *void* is represented as '*transparent and translucent*' [29].

Chi-Ming Lai and Hokoi S. [31] further explained that the solid part constitute thick, heavy, stable and visually non-transparent structural elements, such as solid walls whilst the void part constitutes lightweight and visually transparent structural elements, such as glass, windows and doors. It is important to achieve harmonious design of solid and void parts while designing dynamic façade [31].

Guillermo Q. et al. [32] conducted a detailed literature survey of studies carried out during the last 10 years regarding transparent and translucent solar facades. Figure 2.3 summarizes all the technologies belonging to the family of solar facades [32].

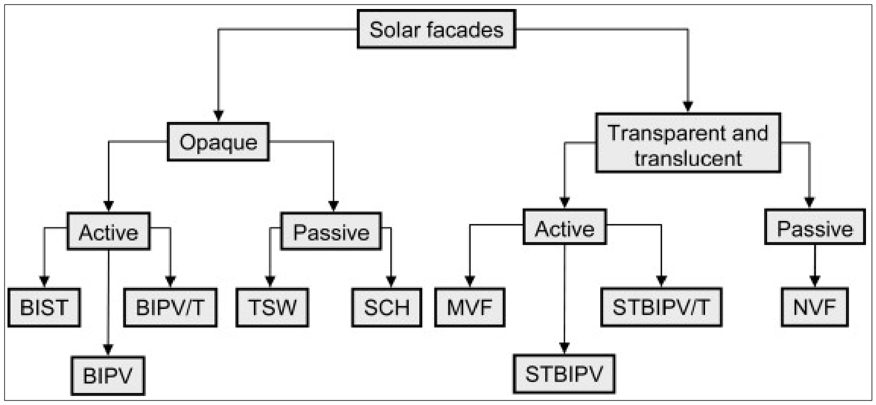


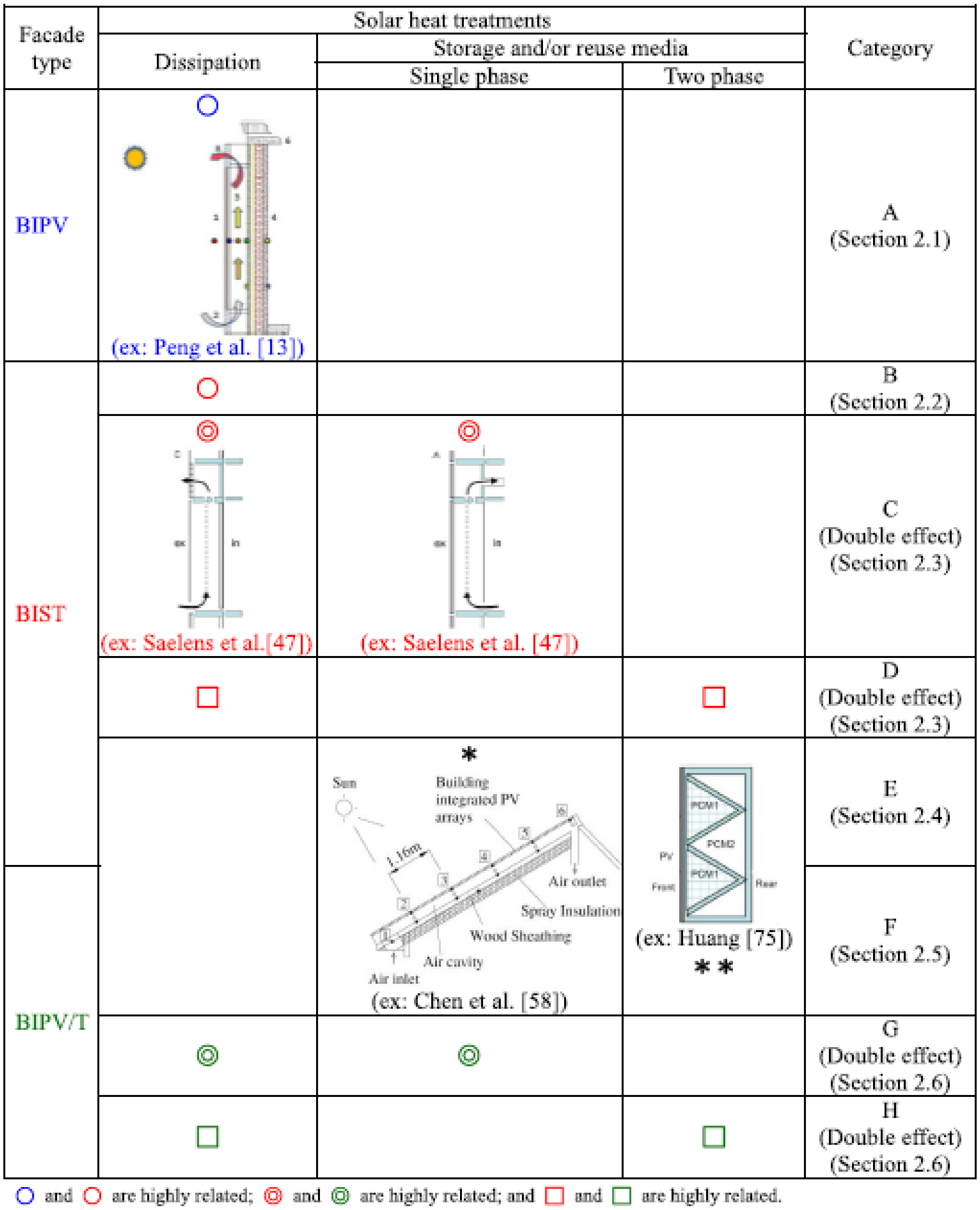
Figure 2.3 Solar facades classification [32].

This research focuses on active opaque as well as active transparent and translucent solar facades.

Type 1: Active opaque solar facades:

A summary of active opaque BIST systems is illustrated in Figure 2.4 [31]. BIST systems effectively remove solar heat gain and maintain a favourable level of thermal comfort especially under hot climatic conditions [31].

Chan et al. proposed the BIST system shown in Figure 2.5 [31]. Saelens et al. [31] proposed another category of BIST systems with a double effect that can be used to eliminate solar heat gain as well as to store and reutilize the solar energy received by the wall surfaces through appropriate mechanisms as shown in Figure 2.6 [31]. These are represented as model C and D in Figure 2.4. Category C BIST systems obtain solar radiation energy received by wall surfaces through the sensible heat exchange of the medium (usually air or water), whereas Category D BIST systems obtain solar radiation energy through the latent heat of the phase change of the medium [31].



Facade type	Solar heat treatments			Category
	Dissipation	Storage and/or reuse media		
		Single phase	Two phase	
BIPV	○ (ex: Peng et al. [13])			A (Section 2.1)
BIST	○			B (Section 2.2)
	◎ (ex: Saelens et al.[47])	◎ (ex: Saelens et al. [47])		C (Double effect) (Section 2.3)
	□		□	D (Double effect) (Section 2.3)
BIST / BIPV/T		✱ (ex: Chen et al. [58])	(ex: Huang [75]) ✱✱	E (Section 2.4) / F (Section 2.5)
BIPV/T	◎	◎		G (Double effect) (Section 2.6)
	□		□	H (Double effect) (Section 2.6)

○ and ○ are highly related; ◎ and ◎ are highly related; and □ and □ are highly related.

Figure 2.4 Classification of active opaque solar facades [31].

Tilmann E. K. [33] explains three new BIST components in his discourse of new BIPV and BIST façade components and is briefly discussed below [33].

- Unglazed solar collector plus heat pump: These are used as low-temperature heat sources combined with heat pumps that are highly efficient and reversible in the heating season and as dissipaters to the surroundings during cooling season. It also requires an additional heat storage medium [33].
- Transparent solar thermal collectors (TSTC): This can either be integrated in a sealed glazing unit or in a closed cavity façade [33].
- Air heating vacuum tube collector (AHVT): This can be used to heat air directly. The heated air is in turn used directly for room heating in winter when combined with solar cooling and heating systems [33].

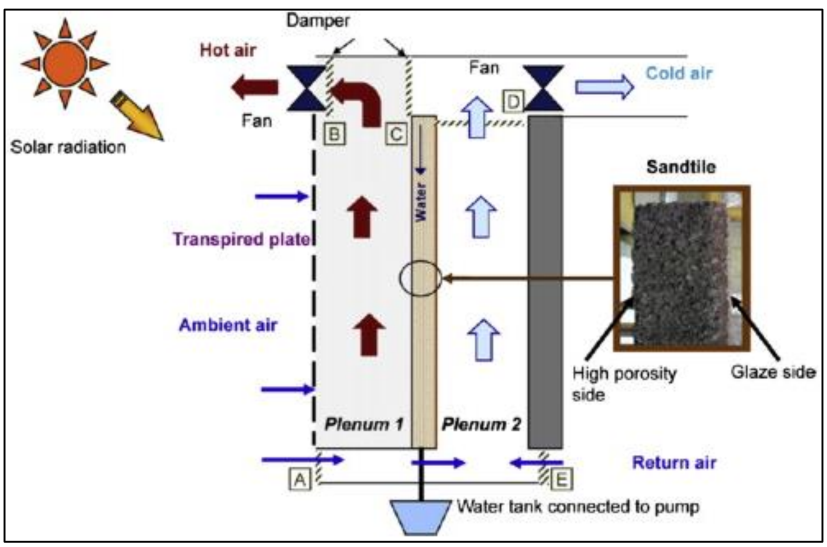


Figure 2.5 Double-plenum outer wall structure proposed by Chan et al [31].

BIPVs are described as PV modules which serve dual functions of building materials and building systems using architectural design methods. BIPVs can be used to generate electricity and can equally replace building materials that were originally designed for use in the locations where the PV modules are installed. This way, the PV modules become a fragment of the building envelope. Thus, BIPV systems are considered “self heat-dissipation" systems [31]. Figure 2.7 illustrates a BIPV system as investigated by Peng et al. [31].

BIPV/T systems are a category oh BIPV which are equipped with a switchable double effect. That is, both self heat-dissipation and heat-storing/reutilizing ability [31]. Figure 2.8 shows a sample of BIPV/T which was designed by Athienitis et al. [31].

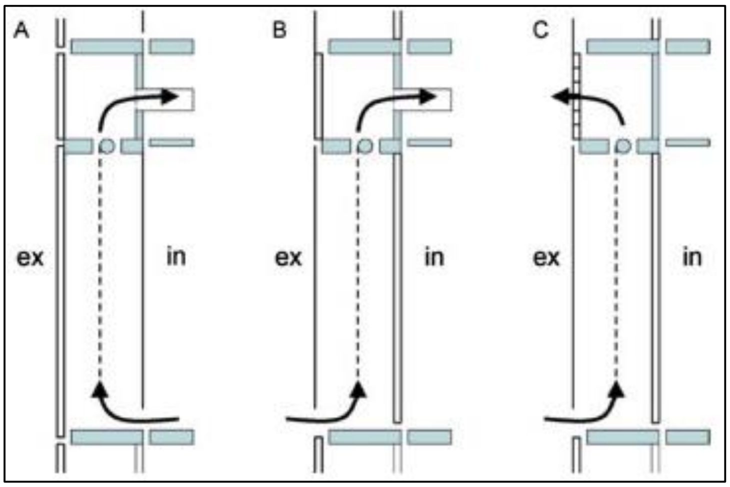


Figure 2.6 Proposed Design by Saelens et al. [28].

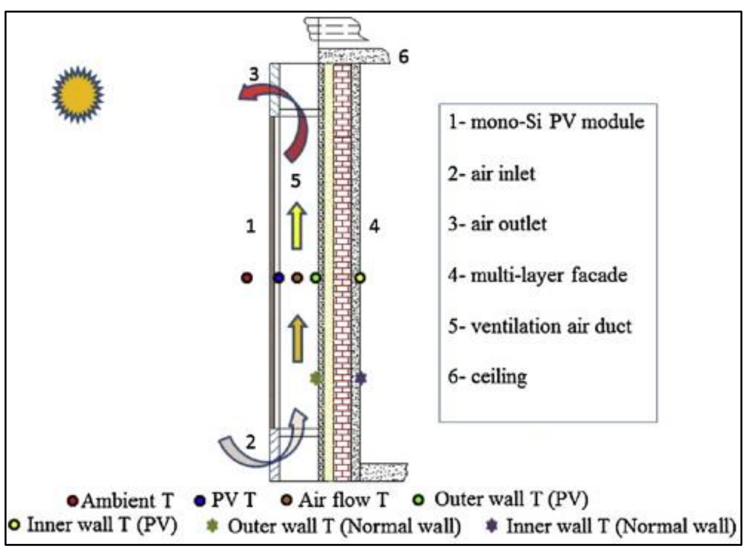


Figure 2.7 BIPV structure as investigated by Peng et al. [28].

Type 2: Active transparent and translucent solar facades:

The authors described both active transparent and translucent solar facades as facades that "are capable of not only absorbing and reflecting incident solar radiation, but also the transfer of direct solar heat gain into the building" [32].

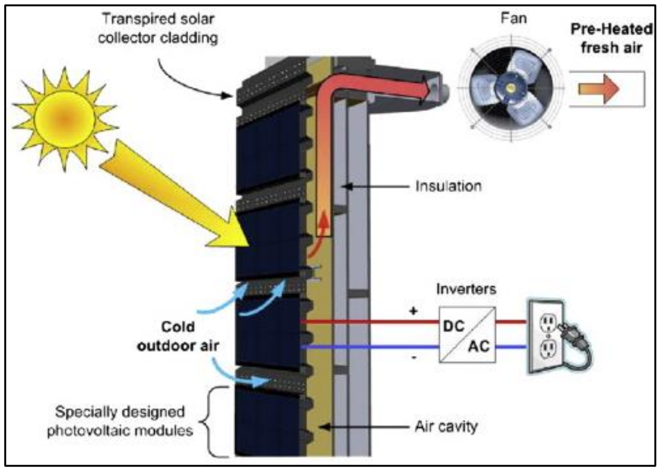
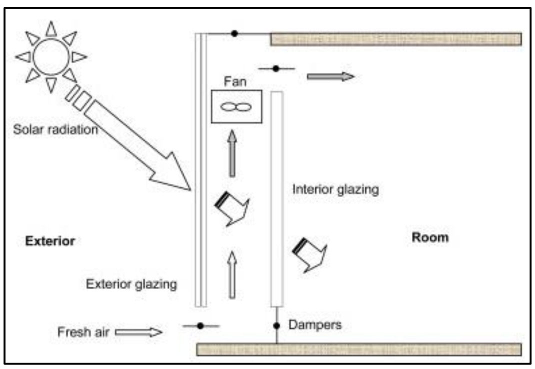


Figure 2.8 BIPV/T system designed by Athienitis et al. [31].

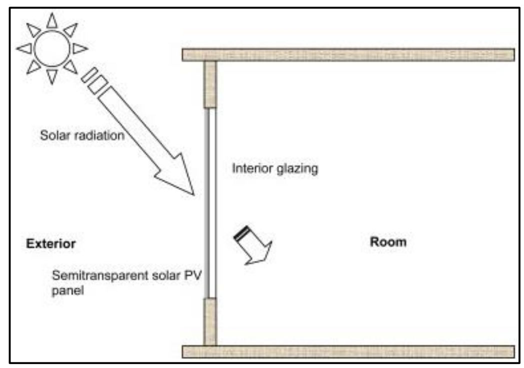
Guillermo Q. et al [32] further stated that active transparent and translucent solar facade is capable of transforming part of the incident sunlight into electricity either directly or via transmitting the thermal energy into the building using electrical or mechanical equipment [32]. Active transparent and translucent solar facades include MVF, STBIPV and STBIPV/T and are briefly described below.

- Mechanically Ventilated Façade (MVF): Guillermo Q. et al define a mechanically ventilated facade (MVF) as a system that "uses a mechanically assisted ventilation system to supply, expel or re-circulate air through a channel located between two transparent or translucent surfaces of the building envelope". The circulated air removes heat from the air cavity reducing the heating and cooling loads of the building based on the required function [32]. Figure 2.9(a) shows a schematic representation of a MVF [32].

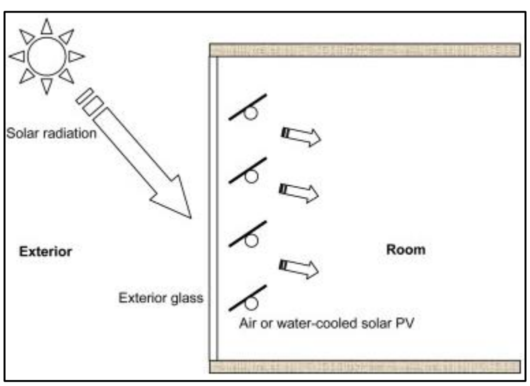
- STBIPV: A semi-transparent building-integrated photovoltaic system (STBIPV) is incorporated into the building envelope which generates electricity through solar photovoltaic modules and allows daylight penetration into the interior spaces [32]. Figure 2.9(b) shows a schematic representation of a STBIPV [32].



(a)



(b)



(c)

(a) MVF

(b) STBIPV

(c) STBIPV/T

Figure 2.9 Schematic diagrams of MVF, STBIPV and STBIPV/T respectively [32].

- STBIPV/T: A Semi-transparent building-integrated photovoltaic thermal (STBIPV/T) system performs a dual function of a BIPV system and that of a BIST system. Thus, allowing daylight penetration into the interior spaces of a building [32]. A schematic representation of a STBIPV/T system is illustrated in Figure 2.9(c) [32].

Responsive architecture is commonly used to symbolize the performative role of computational systems and kinetics embedded in architectural form [34]. Lijida Grozdanic [34] viewed responsive architecture as the most rapidly evolving field of disciplinary practice. Whether the idea is motivated by a sustainability approach or is restricted to pure fascination with technological innovation, the interest in responsive design has become a global part of the contemporary architectural discourse [34]. Although there may be hidden costs and performance issues, some of the state-of-the-art built projects attest to the technological advancement and different cutting-edge trends in façade design are presented as case studies. Various classifications of dynamic facades can be achieved through different ways as described by multiple case studies below.

Case study1: ***User-controlled Dynamic Facade***

https://www.youtube.com/watch?v=rAn4ldWjw2w [34]

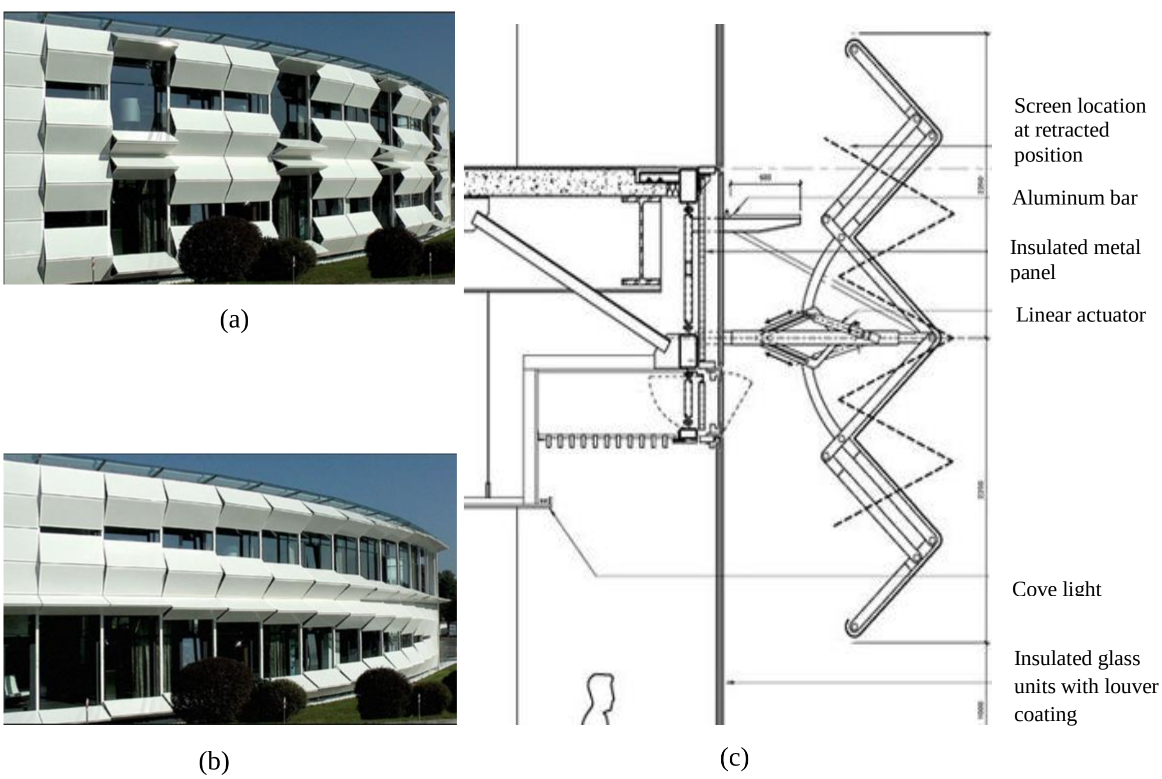
Kiefer Technic Showroom was designed by Ernst Giselbrecht + Partner as a mixed-use building housing office and exhibition spaces [35]. The building not only continuously showcases new facades as the day progresses, but also regulates the building’s internal climate in terms of thermal and visual requirements, maximizes daylight utilisation and overall cooling and heating demands of the building. The envelope consists of several layers including aluminium posts and Exterior Insulation and Finish System (EIFS)-façade transoms encased in white plaster. The building is characterised as a dynamic building as it comprises of 112 perforated aluminium panels that are electronically controlled by 54 motors. These movable panels create a changeable shell that transforms the conventional building appearance from a solid volume to a sparkling and exquisite dynamic configurations [36-38]. Although the façade itself functions as a shading device, its ability to offer users the alternative to adjust the panel's angle and amount of transmitted light to the interior earns it the name 'user-control dynamic façade'. This is achieved by controlling the desired number of the noise-free aluminium panels of the façade which could be set on a continuous pattern [37]. However, there is inadequacy of information to justify that the energy this façade saves while enhancing thermal and visual comfort in the building, is less than the energy consumed in operating the façade. Figure 2.10 (a-c) shows section and views of User-controlled Dynamic Facade of Kiefer Technic Showroom [39].

Case study 2: *Dynamic Honeycomb Façade*

https://www.youtube.com/watch?v=BSEVoFi9MpQ [40]

https://www.youtube.com/watch?v=t5tLY9lyxI4 [41]

Designed by Aedas Architects, Al Bahr towers is home to the new Abu Dhabi Investment Council^{TR}. The twin towers are cladded with an exceptional vibrant shading system that is considered to have tested the limits of dynamic design. The Mashrabiya (a traditional Islamic lattice shading system) inspired the façade design. The concept of Mashrabiya was entirely modernized to respond to the ever changing weather conditions of the UAE [35]. The two 25-storey towers soaring to a height of 145 meters each provide 70,000 square meter of office space and covered with 2000 mobile panels [41]. The curved cylindrical glass towers' screens respond automatically to solar radiation by opening once no direct sunlight is reaching the surface and closing when it is otherwise [41, 30]. The sun screen stands on an independent frame two meters away from the perimeter of the building. In order to reduce solar gain, each triangle of the screen is coated with fiberglass and is programmed to respond to the sun's movement. The ability of the screen to filter light as it penetrates through provide the design team with endless alternatives in the choice of glass [42].

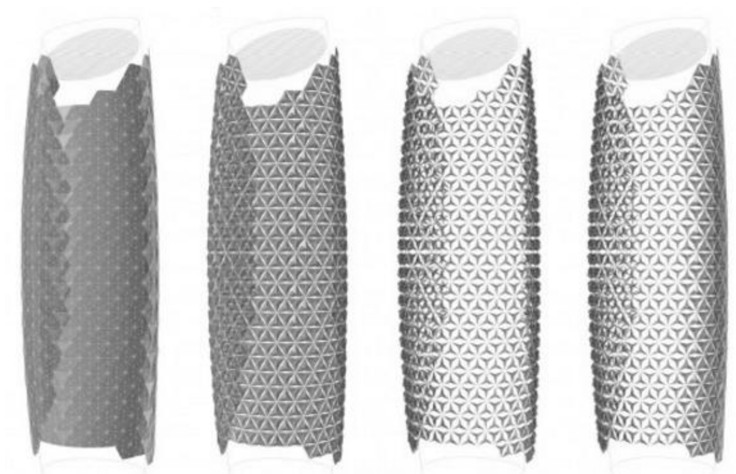


(a) Façade provides both shading and daylight. (b) Façade provides both shading and daylight. (c) A cross section across the dynamic façade showing its component details (modified).

Figure 2.10 Views and section of User-controlled Dynamic Facade [39].

As part of its green credentials, each of Al Bahr towers is claimed to reduce the buildings' air conditioning load in the work space by 50% which results in reducing the amount of CO_2 emissions by 1,750 tons annually. These achievements earned the building a Leadership in Energy and Environmental Design (LEED) silver rating [41]. Figure 2.11 (a-c) shows various images of *Dynamic Honeycomb Façade* utilized in Al Bahr towers [35, 43].

(a)



(c)

(b)

(a) Façade opens and closes to provide daylight and shading respectively.

(b) Façade construction showing its details.

(c) Façade model showing closed, half-closed and open models.

Figure 2.11 Images of Dynamic Honeycomb Façade [35, 43].

Case study 3: ***Ethylene tetrafluoroethylene (ETFE) façade***

https://www.youtube.com/watch?v=EHpjtMlKWzs [44]

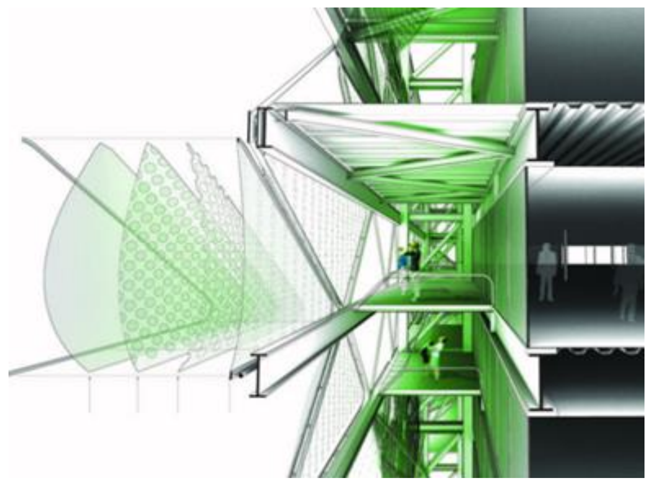
This Ethylene tetrafluoroethylene (ETFE) façade was designed by architects at cloud 9 in association with Vector Foiltec to respond to the changing weather conditions of the region [35, 30]. As the name implies, Media-ICT was designed to serve as center point for businesses, media sensors as well as institutions in ICTs [45]. The façade opens to allow daylight in winter and closes to block unwanted solar gain and glare in hot summer. This system is equipped with temperature, humidity and pressure sensors. These sensors continuously work to determine immediate changes in environmental conditions and adjust accordingly in order to enhance the energy utilization of the building [35, 30]. Overall, the façade was cladded with 2,500 m^2 of ETFE material which in turn provides energy savings of 20% in the building [46]. The Media-ICT also achieves a total of 95% CO_2 reduction through the use of district cooling and clean energy, utilization of solar photovoltaic roof the use of responsive ETFE sun filters, as well as the incorporation of various smart sensors. These achievements and more earned the building to be considered as almost a net-zero building [47]. Interestingly, in 2011, this office building emerged as world building of the year in world Architecture Festival held in Barcelona, Spain [48]. However, the disadvantage of this façade is its delay in reacting to the ever changing environmental conditions as a complete cycle of opening and closing takes at least an hour [30]. Figure 2.12 (a-c) illustrates images of Façade for the Media-ICT Building [18, 48].

Case study 4: ***Advanced Adaptive Façade***

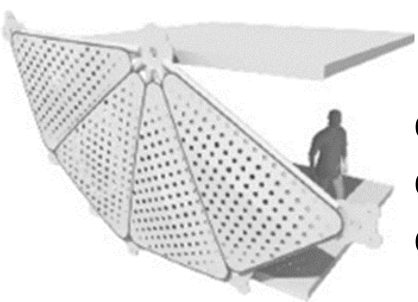
https://www.youtube.com/watch?v=C2_H8peGhMw

One ocean was designed by the Austrian firm soma as a proposal for the EXPO 2012 held in South Korea. So far, it remains one of the largest adaptive constructions ever erected and imitates the whale's baleen filter [35, 50]. Designed to maximize natural ventilation, the design of this gigantic structure won the first prize in an open international competition in 2009 [51-52]. Its dynamic façade, comprises 108 lamella made up of Glass Fiber Reinforced Polymer (GFRP) supported both at the top and bottom edges [35, 52].

(a)



(c)



(b)

(a) The ETFE Media-ICT building.

(b) How perforated ETFE panels respond to unwanted solar radiation.

(c) Isometric projection of façade components.

Figure 2.12 Views of ETFE facade [30, 48].

Characterized by its fish-like features, this highly advanced façade is capable of changing into various animated patterns. The dynamic effect is an effortlessly changing envelop that is flawlessly incorporated in to the overall skin of the pavilion [52]. The gill-like lamella ranging from 10 through 43 meters high controls the amount of daylight penetrating in to the building [51]. Roof-top solar panels power not only the movement of the 108 lamellas but provide two-thirds of the total energy consumed by the building systems annually [53]. The façade responds to changing environmental conditions by opening and closing where necessary through elastic bending. The façade has a total of 216 corresponding servo motors. During strong winds, all the servo motors close except 13 lamellas [35]. However, the facades' movement is regarded as more aesthetically oriented rather than been energy performance oriented [30]. Figure 2.13 (a-c) presents images of the façade [49, 53].

(a) (b)

(a) The One Ocean building. (b) Images showing how the façade operates and a cross-section of a panel.

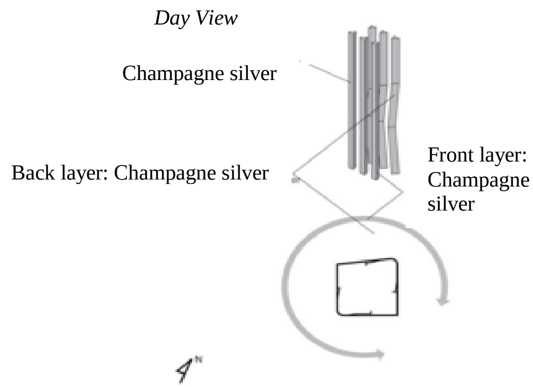
Figure 2.13 Images of Advanced Adaptive Façade [46, 53].

Case study 5*: Dynamic Optical Façade*

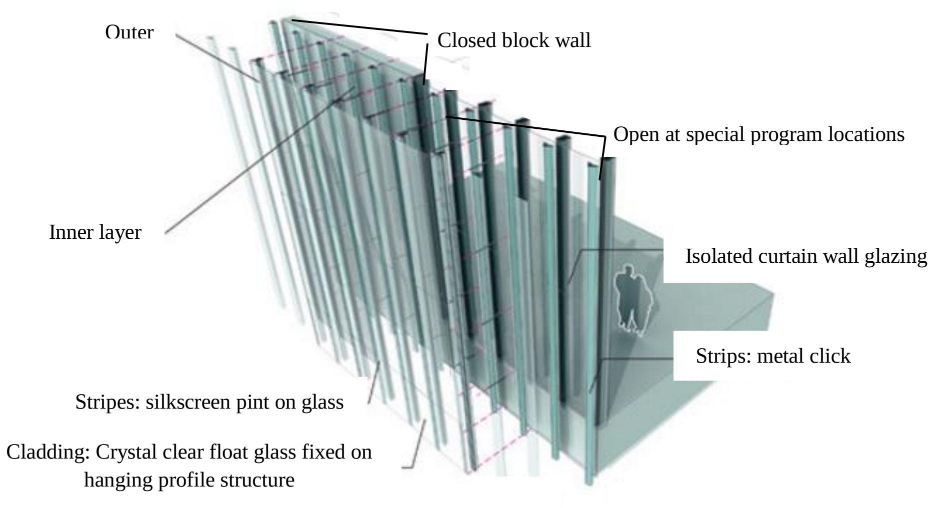
https://www.youtube.com/watch?v=w17dwoG40TU [54]

Galleria centercity building was designed as United Nation's (UN) studio. The building houses department store with a variety of functional facilities. The double layered façade creates an optical illusion with the help of light fixtures. The façade constitutes two layers of modified aluminum profiles placed on top of a layer of composite aluminum cladding.

(a)



(b)



(c)

(a) Galleria Centercity Building. (b) Day view of the façade showing its layers. (c) Isometric view showing different components of the façade.

Figure 2.14 Views of Dynamic Optical Façade facade [57].

The different profiles of these aluminum layers create a varying wave-like effect depending on the position of the observer and is observed on the envelope. This wave-like effect creates zones of different resolution and detail and is complemented with light back projections [35, 55]. The openings of the 66,000 m^2 building provide natural lighting to the building interior. The façade lamellas prevent the passage of direct sunlight in to the building. This reduces the total building's energy demand for cooling purposes. Additionally, the use of light finishes throughout the building interior minimizes the need for artificial lighting to a certain extend [56]. Figure 2.14 (a-c) shows different views of the studio [57].

Case study 6: *Kinetic Wind-driven Façade*

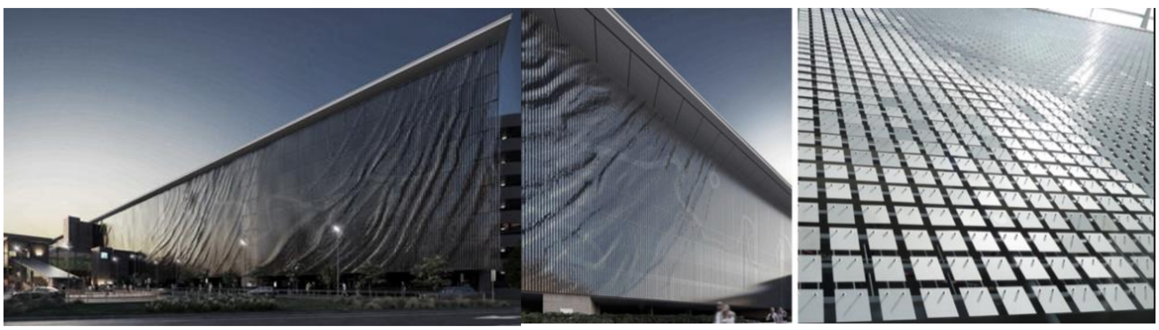
https://www.youtube.com/watch?v=sbq6HqqiXcQ [58]

In conjunction with Urban Art Projects (UAP), artist Ned Kahn designed a dynamic, wind-driven façade for a short-term domestic car park at the Brisbane Airport, Australia. Small and individually moving aluminum panels were mounted over a steel substructure. This provides a dynamic shading system for the interior of the terminal's car park [35]. The wind-powered façade comprises of over 250,000 installed aluminum panels. Wind provides the dynamic pattern of motion on the façade without wasting energy. This kinetic façade proves to be sustainable by blocking direct solar gain and improving overall passengers' thermal comfort without wasting energy or generating CO_2 [59-60]. The 8 storey wind-driven façade represents the way light reflects off moving water and covers only one side of the terminal [35, 58]. Figure 2.15 (a-c) shows the various images of the Façade [35, 58-60].

Case study 7: *Flare*

https://www.youtube.com/watch?v=rMzoMyU0YQ4&list=PLA5E9159F0A93C4BB [61]

Flare is a kinetic reflection membrane. It is a composition of 3-dimensioal and efficient geometric flakes which are dynamically rotated in a rippling motion [62-63].



(a) (b)

(a) Brisbane Domestic Terminal Car Park.

(b) The effect of the façade on the building and arrangement of aluminum panels.

(c) The interior frames holding the panels of the façade.

(c)

Figure 2.15 Kinetic Wind-driven Façade [35, 58, 60].

It was designed by Berlin's WhiteVoid in 2008 [64]. Flare system consists of tiltable metals flakes that are individually operated by a machine-controlled pneumatic cylinders [61, 63]. Each unit of flare comprises 16 respective components. Components are obliquely positioned at varying adjacent angles and are rotated from one fixed axis to achieve a remarkable set of effects [62]. Flakes reflects either the bright sky or the darker ground. A downward tilted flake appears as a dark pixel. In contrast, an upturned flake reflects the bright sky [61]. Unlike other dynamic facades, flare can be mounted on any desired building as an additional system. Flare is activated by a computer system upon receiving motion and occupancy alert from sensor systems mounted within and outside the building [63-64]. "Flare enable the building system to operate like a living skin, allowing it to express, communicate and interact with its environment" [65]. In other words, it turned the building façade from static to a permeable dynamic membrane [64]. Figure 2.16 (a-c) illustrates different views of the Berlin's WhiteVoid Flare [66].

(a) (b)

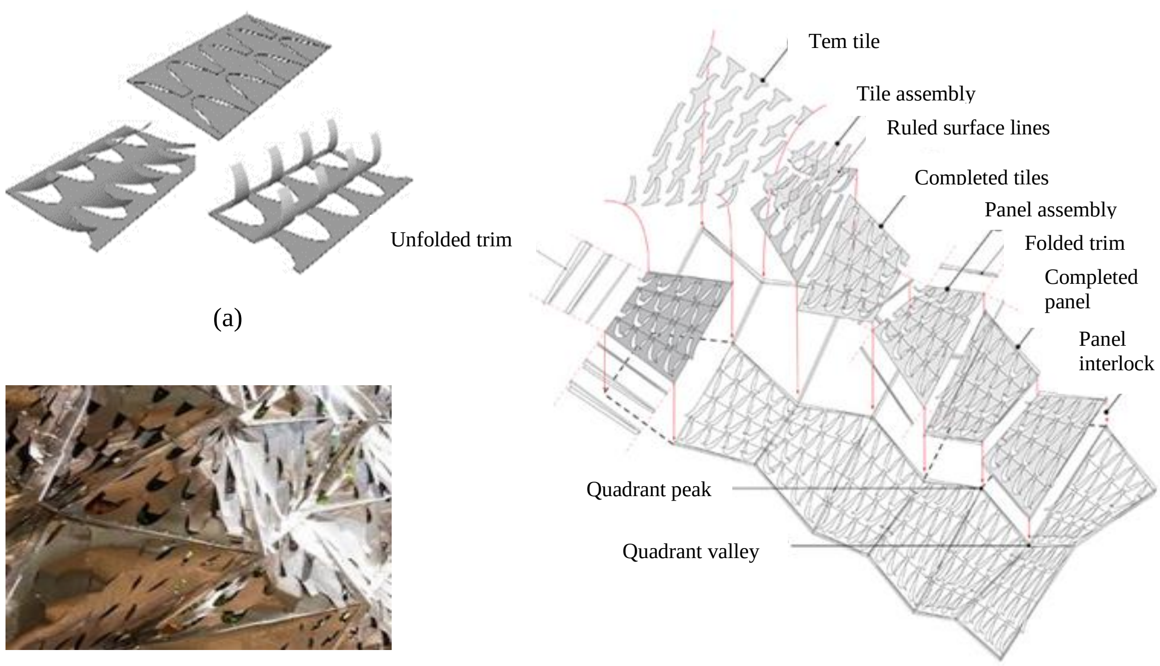
(a) A building with flare mounted. (b) The façade and a Flare showing 16 detailed flakes (components).

Figure 2.16 FLARE [66].

Case study 8: *Bloom*

https://www.youtube.com/watch?v=V17Lp1X0_ao [67]

Bloom is an environmentally responsive installation. It is a shell-like form designed by Los Angeles-based DOSU studio architecture headed by Doris Kim Sung. Bloom is a 20-foot canopy installed at the Materials and Applications gallery in Los Angeles. The light weight and flexible structure was made primarily out of smart thermo bi-metal plates. Thermo bi-metal is a sheet metal which expands when heated [68-69]. Thermo bi-metals are also regarded as panels that comprises two thing layers of metals of varying thermal properties laminated together [30, 69]. Approximately, Bloom comprises 14,000 different laser-cut tiles of thermo bi-metal tiles in which no two have same heat coefficient [70]. Bloom responds to environmental conditions by opening and closing the metal plates as desired [69].



(a) Bloom’s bimetal panels. (b) Installed different bimetal panels. (c) Detailed arrangement of the bloom’s components.

Figure 2.17 Bloom [30, 70].

When exposed to the heat, the structure responds by providing shades and ventilation to the required areas [68]. Thermo bi-metals “start crawling at about 7^0C and continue till about 400^0C” when exposed to heat [67]. The self-supported structure signifies how building materials can respond to the changing environmental conditions without any mechanical aid. Bloom also shows how building materials can incorporate changeability to static structures [70]. When installed in a building, Bloom will reduce total load on mechanical systems. That is, it will minimize CO_2 generation and promote green and sustainable environment. Figure 2.17 (a-c) illustrate different models and images of the Bloom [30, 70].

Case study 9: *Adaptive Shading Systems*

https://www.youtube.com/watch?v=drbBLu5KWwY [71]

Aldar central market provides spaces for shops, hotels, restaurants and offices. It is an ecologically sensitive low-rise market with a vibrant roof-top gardens for the public. Aldar’s incredible sliding walls and roof enhances daylight and natural ventilation in to the market thereby reducing energy costs [71-73]. This sliding panel - roofing system was developed by Hoberman Associates and uses a hybrid mechanical system [30]. It was designed in order to enhance the architectural design of the main market accomplished by Foster + Partners. The design of the panels is based on octagonal forms that was inspired by both traditional zellij tilework and mathematical geometry. The steel roof system covered 1000 m^2 and constitutes 8 number of operable units having 7 layers that are sandwiched into each module [77]. Each unit is driven by a servo motor with custom array control. Each whole unit of the interactive roof consists of several openings that are controlled by a single drive arm. This way, the system remains economic and efficient at the same time [74-77]. The shading system promotes sustainable practice by ensuring reduced solar gain and glare, enhancing natural ventilation and daylight, providing adequate control of shading and reduced energy costs [72-73]. Figure 2.18 (a-c) shows various images of the roof system [78].

(a)

(b)

(c)

(a) Aldar Central Market, UAE.

(b) Closed roof system to block solar gain.

(c) Half-closed sliding roof providing the required daylight.

Figure 2.18 Adaptive Shading Systems [78].

Case study 10: ***Advanced Responsive Façade***

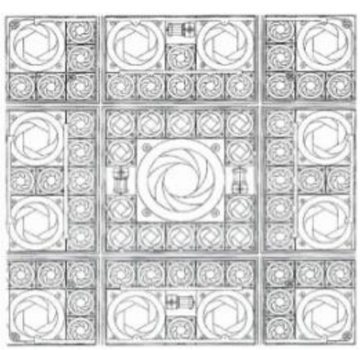
https://www.youtube.com/watch?v=5DEEjTlJl8E [79]

Arab World Institute is a 25,000 m^2 building that houses offices, museums, cafeteria, library, conference rooms and auditorium. Built in 1987, the breathable façade was designed based on the principle of mashrabiya (an archetypal element of Arabic architecture used for privacy and sun's protection).

The aluminum and glass sun screen occupies the south façade of the building. The façade incorporates between 27,000 - 30,000 light sensitive, advanced responsive diaphragms assembled in 113 panels and operated on the principle of a camera lens. The gigantic 30 by 80 m facade regulate the amount of light entering the building. The façade's diaphragms contribute in cooling the whole building and regulate the amount of light into the building [30, 79-81]. They provide 10 to 30% of daylight into the building and are controlled via a photovoltaic sensor. The advanced responsive metallic sun screen provide both privacy and protection from the sun.

(a)

(b)



(c)

(a) Arab World Institute.

(b) Installed diaphragms forming the adaptive façade.

(c) Façade details showing a single Diaphragm.

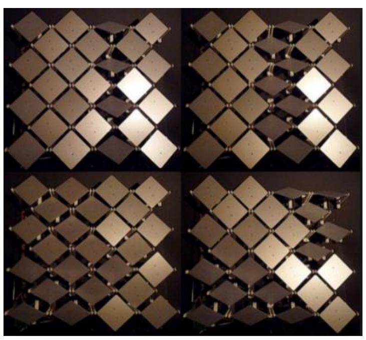
Figure 2.19 Advanced Responsive Façade [82].

Different shapes are created during the various phases of the lens as the façade opens and closes. A changing geometric pattern is achieved and perceived as light and void as the facade allows and blocks view as desired. Solar gain is simply moderated by controlling the opening sizes of the panels thereby saving great deal of energy. The originality and quality of the design won Jean Nouvel awards for Equirre d'Argent for Architecture and Aga Khan Award for Architecture in 1987 and 1989 respectively. While the façade remains functional from environmental control perspective, the visual elements continue to create an incredible aesthetic [80-81]. However, due to high maintenance cost of the façade's mechanical components, the system is currently inoperable as it requires high operating cost [30, 79]. Figure 2.19 (a-c) shows plan, sections and different views of the façade [82].

Case study 11: ***Adaptive Fa[CA]de***

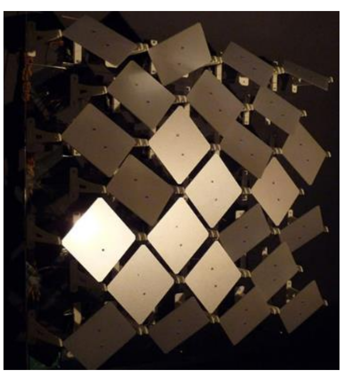
https://www.youtube.com/watch?v=K-n5L_6i9_M [83]

Adaptive Fa[CA]de is a responsive cellular automata façade that is trained by Artificial Neural Network (ANN) [84]. Proposed by Marilena Skavara in 2009, the façade explores the functional possibilities and performance characteristics of Cellular Automata (CA). Additionally, the systems control-façade also incorporates the use of Genetic Algorithms (GA) [30, 83]. The façade constitute a changeable skin that responds to the light levels of the surrounding. Build upon complex CA, the façade provides an optimum intensity of light to the interiors. The self-replicating system also results to an aesthetically –oriented kinetic façade. So far, the project has been awarded with EUROPRIX Quality seal 2010 [84]. The major problem ANN attempts to solve is continuous training of the system in order to respond to various sun positions throughout the year [85]. The façade constantly trains itself from the history of its errors and achievements. Rodrigo Velasco et al indicated that this is a predictable solution to a stationed building using sun path diagrams. However, where this system is employed on a mobile structure, a GPS system could be incorporated to enable the façade function with the help of a constantly updated data. Several concerns must be addressed to make this façade a more viable solution [30]. Changing geometry of the system regarding reflections and quantitative definition of solar access are some of the system's drawbacks [54].



(a)

(b)



(c)

(a) Different movements generated in the façade.

(b) Movements generated during a laboratory testing.

(c) Detailed components of the façade.

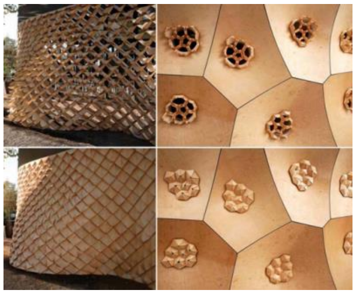
Figure 2.20 Adaptive Fa[CA]de [86].

Nevertheless, Rodrigo Velasco et al concluded that interesting results could be obtained where the system is employed in locations with varying microclimates as a result of physical obstructions [30]. Figure 2.20 (a-c) shows various images of the proposed cellular façade [86].

Case study 12: *HygroSkin-Meteorosensitive Pavilion*

https://www.youtube.com/watch?v=ArFtgLY-YBY [87]

Similar to the *Bloom*, the HygroSkin-Meteorosensitive pavilion is also a climate responsive architectural project. It was designed by Archim Menges et al. from the Institute of Computational Design (ICD), University of Stuttgart, Germany [30, 87]. The dimensional instability of wood to moisture and the interrelationship between computational morphologies as well as robotic manufacturing were combined to develop the architectural skin. The system depends on a material embedded control system and reacts to relative humidity levels rather than heat. The skin expands and contracts in response to relative humidity levels without any mechanical equipment or operational energy [88-89]. *"It is a question of surrendering to the wood, then following where it leads by connecting operations to a materiality, instead of imposing a form upon a matter"* [89]. As the humidity level increases, - for instance from about 35-40% to about 75-80% - the moisture content adsorbed by the wood cells make them expand. This expansion triggers a shape change and the morphology opens. As the humidity level falls, the system closes automatically. Interestingly, the hygroscopic material is metabolism independent and requires no supply of operational energy. Algorithms were used to produce automated process to generate this complex form [87-89].



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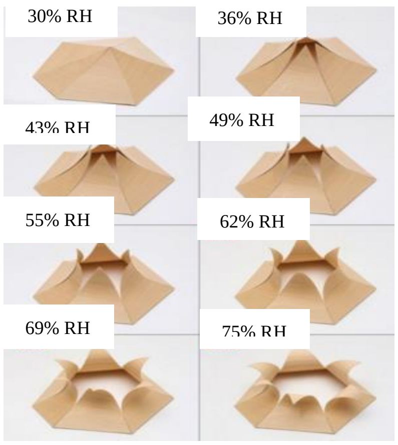


(c)

(a) Façade response based on relative humidity levels.

(b) Interior space showing closed facades and façade's response during a laboratory testing.

(c) Response of wood cells based on relative humidity levels.

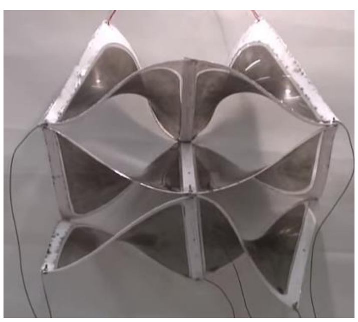
Figure 2.21 HygroSkin-Meteorosensitive Pavilion [90].

The system is widely in use across Europe. In a nut shell, HygroSkin-Meteorosensitive Pavilion is a sustainable project that generates zero CO_2 and ensures great energy savings. Figure 2.21 (a-c) shows the morphological pattern of the system [90].

Case study 13: ***ShapeShift Electroactive Polymer Façade***

https://www.youtube.com/watch?v=4XGVMXCxBNA [91]

ShapeShift was designed by Manuel Kretzer et al. and explores the possibility of utilizing ElectroActive Polymers (EAP) at an architectural scale [30, 92]. EAPs are ultra-light, extremely flexible, thin and transparent material that changes its shape without the aid of mechanical actuators. EAPs are also characterized with both high deformation potential and speed as well as low density and enhance resilience. EAPs convert electrical power into kinetic force and are used to create responsive surfaces that dynamically react to external environment. Another advantage of EAPs is that they can strain up to 380% and can be shaped to any desired form [92]. The components of each panel are built of three layers, in the middle a pre-stretched thin acrylic film is painted with conductive powder on both sides and protected with silicon insulation layers on each face. Through the transmittance of electricity across the conductive coatings of the inner pre-stretched layer, the material expands to form a flat shape; otherwise it stays in its doubly curved pre-stretched shape [30, 91]. This smart one-story solar strands allow, filter and block the sun where necessary, positioning themselves as if following its path.



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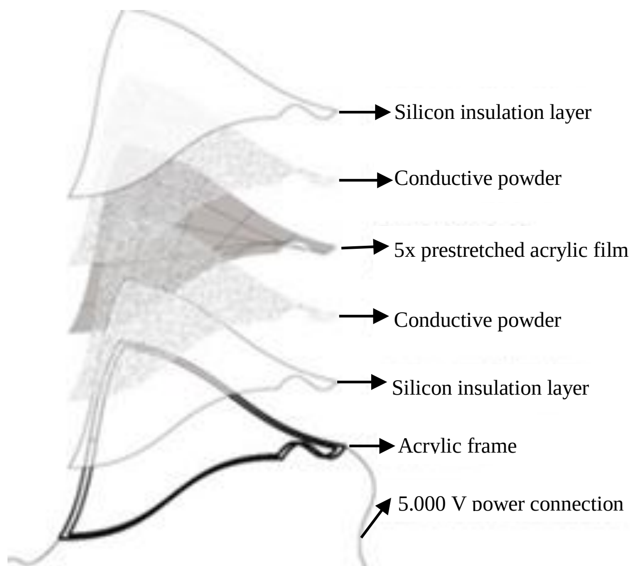


(c)

(a) Expanded panels of the Façade. (b) Collapsed panels of the Façade.

(c) Details of components of a panel.

Figure 2.22 ShapeShift Electroactive Polymer [94].

When shading is not required, the strands collapse and align with the curtain wall mullions, thus allowing clear view of the outside [93]. Numerous drawbacks are that the existing configurations are considered to be quite fragile, unstable and require considerable energy [30]. Figure 2.22 (a-c) shows images of ShapeShiftt Electroactive Polymer Façade [94].

Case study 14: *Hexagonal Dynamic Façade*

https://www.youtube.com/watch?v=8Z3NoDoG_Qw [95]

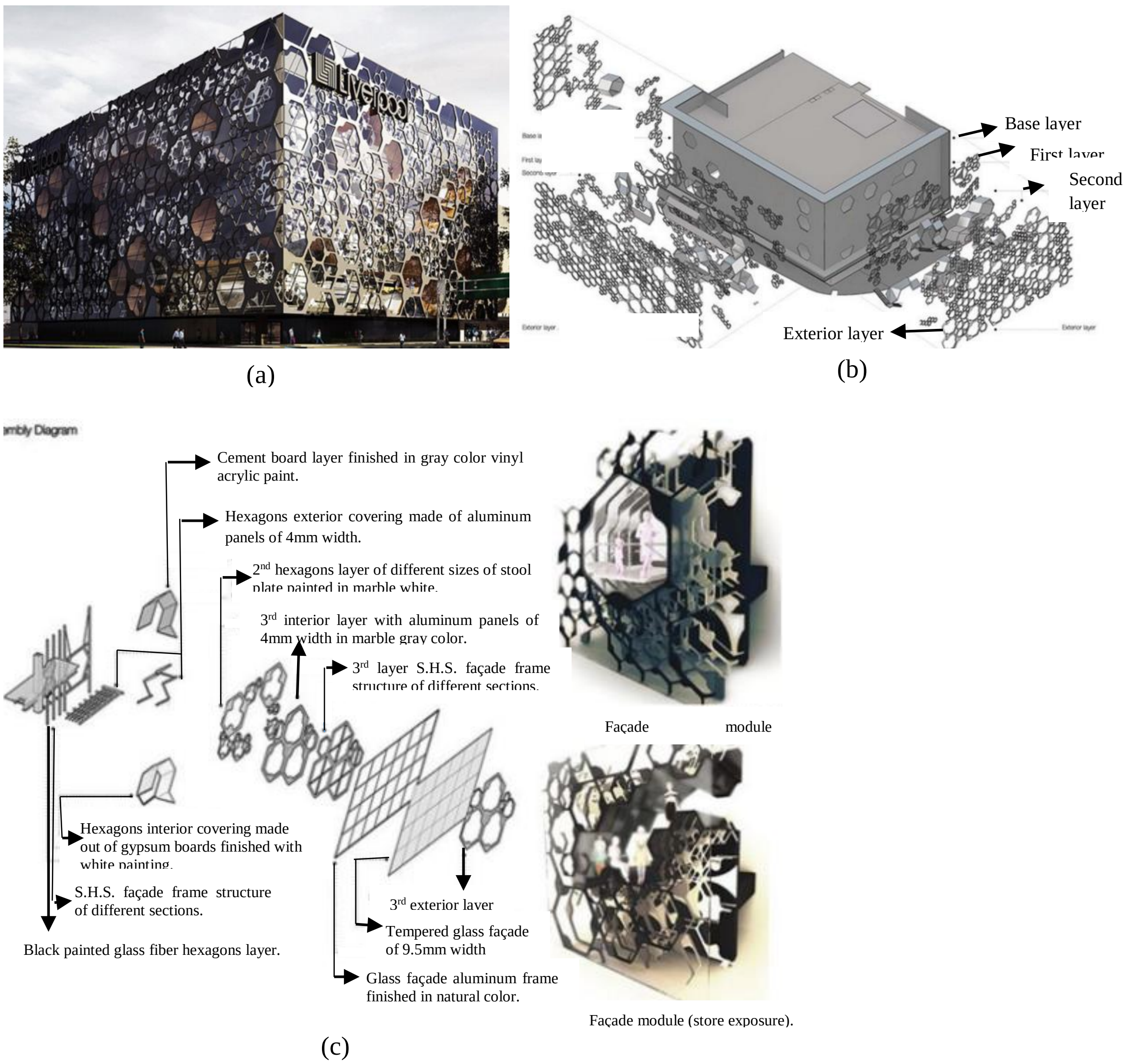
This façade is utilized in *Liverpool Department Store*. The 2400 m^2 hexagonal dynamic façade was designed by rojkind architects in 2010 and built in the Mexico City of Mexico. The skin measures 2.8 m in depth and is composed of three layers of fiberglass, steel, aluminum and glass [95-96]. The permeable habitable façade provide interactive atmosphere between the user and the passer by. Occupants access and exits the resulting spaces within the façade using stairs and ramps [97]. The hexagonal mesh creates a dynamic surface with endless geometries highlighted by interior light that change based on the observer's perspective. The façade was recognized in the Progressive Architecture Awards and has won the 2014 pa citation award [95-96]. Figure 2.23 (a-c) presents images and details of the award winning façade [96, 98].

Case study 15: *Lighting Smart Façade*

https://www.youtube.com/watch?v=ucu4rsc7HzY [99]

https://www.youtube.com/watch?v=O3pBMaQ41nA [100]

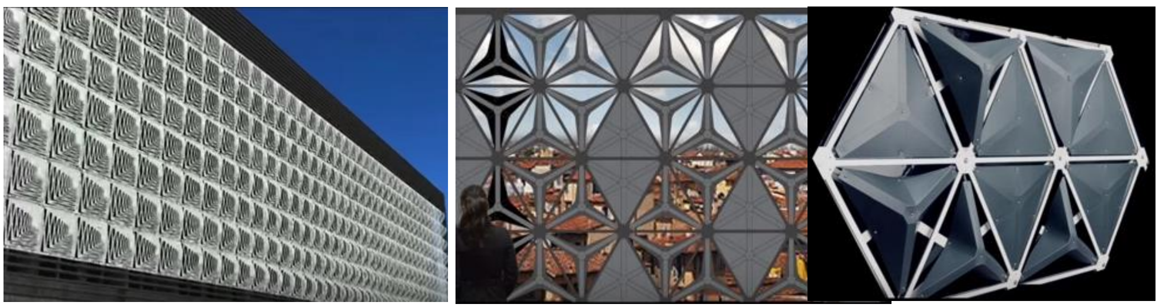
This is students' project developed by Arman Saberi (Assistant professor). The project was regarding an interactive façade for natural light regulation. Memory wire and light sensors that react to temperature and light respectively were integrated in the model.



(a) Liverpool department store, Mexico. (b) Exploded axonometric view of the façade (c) Façade assembly.

Figure 2.23 Hexagonal Dynamic Façade [96, 98].

The mechanically controlled system regulates light, makes shadow and blocks direct view from the outside. Street screen has additionally been added to the façade to add aesthetical value [99].The façade was developed at the professor G.Ridolfi's "Environmental Design Lab" class, University of Florence [100]. Figure 2.24 (a-c) shows images of the facade [100-101].



(a) (b) (c)

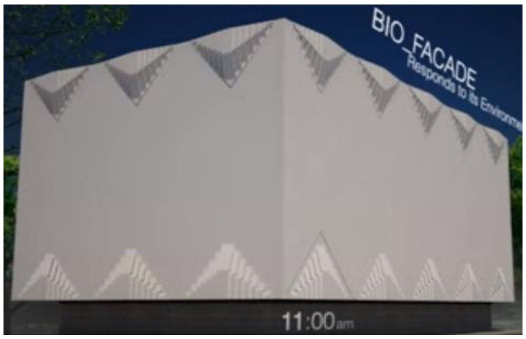
(a) Lighting smart facade. (b) Effect created by the façade. (c) Façade model during testing.

Figure 2.24 Lighting Smart Façade [100-101].

Case study 16: ***Bio Façade***

https://www.youtube.com/watch?v=P6RHFDgeFTA [102]

Bio façade was designed by Mathew Hunter to respond to its environment in an attempt to save energy. Bio facade calculates the elevation angle of the sun (location, time and date = solar time = declination angle) and responds accordingly. For instance, at 12pm mid-summer, the façade opens to provide shading for the glazing from direct solar gain when the sun is high. Whilst at 12pm mid-winter, the façade closes to provide shading for the glazing from direct solar gain when the sun becomes low. Furthermore, in mid-winter, the facade opens to allow for daylight and acceptable morning and evening solar gain due to low-sun angle. While in mid-summer, the facade closes to block morning and evening solar penetration as the sun angle become higher [103]. Figure 2.25 (a-c) shows the sequence of changes in the façade appearance as the solar angle changes [102, 103].



(a)

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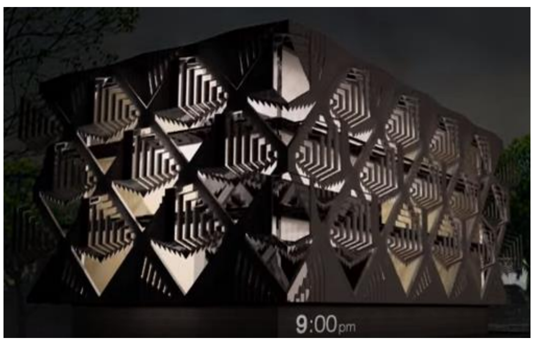


(c)

(a) Bio façade responds to its environment by closing to block solar penetration.

(b) Façade responds to its environment by opening to allow daylight penetration.

(c) Façade opens to allow occupants view the exterior.

Figure 2.25 Bio Façade [102, 104].

A summary of the characteristics of the investigated dynamic facades is summarized in Table 2.1. The Table provides a summary of the merits and demerits of each dynamic façade discussed as a case study in this literature review. It also provides an insight into sustainable practices such as enhancement of daylight utilization, improved overall thermal comfort and optimization of energy utilization in buildings. The table equally highlights the possibility and suitability of adopting such facades in hot climatic regions of the world (such as Saudi Arabia).

Table 2.1 Advantages and Disadvantages of investigated dynamic façades.

Façade Type	**Merits and Demerits**
User-controlled Dynamic Facade (Case study 1)	Merit: • The façade optimizes the building's internal climate.
Dynamic Honeycomb Façade (Case study 2)	Merits: • Reduces building's solar gain by 50%. • Limits the amount of $C0^2$ by 1,750 tons a year. • LEED accredited (Silver).
Ethylene Tetrafluoroethylene (ETFE) Façade (case study 3)	Merits: • Optimization of building's energy use through the use of temperature, humidity and pressure sensors. Demerit: • Delay in reacting to changes in environmental conditions.
Advanced Adaptive Façade (case study 4)	Merit: • It is resistant to strong winds. Demerit: • It is viewed as more aesthetically oriented rather than energy efficiency.
Dynamic Optical Façade (case study 5)	Merit: • Creates aesthetically pleasing environment especially at night.
Kinetic wind-driven façade (case study 6)	Merit: • The façade provides kinetic shading for the interior.
Flare (case study 7)	Merits: • Reduces solar gain. • Allows a building to express, communicate and interact with its environment.
Bloom (case study 8)	Merit: • No operational energy required. Demerit: • It is less likely to be applicable in façade design due to climatic conditions of KSA
Adaptive Shading Systems (case study 9)	Merits: • Allows adequate daylight access. • Blocks solar gain as required. Demerit: • It is most likely to require high operational energy.
Advanced Responsive Façade (case study 10)	Merits: • Provides privacy and outdoor visual comfort. • Allows daylight penetration. Demerit: • It has high maintenance cost.
Adaptive Fa[CA]de (case study 11)	Demerit: • It is still under laboratory investigation and development.
HygroSkin-Meteorosensitive Pavilion (case study 12)	Merits: • It is metabolism independent. • Does not require the supply of operational energy. Demerit: • It is not compatible with hot-humid climates.
ShapeShift Electroactive Polymer Façade (case study 13)	Merit: • The façade allows, filter and block the sun where necessary. Demerit: • Requires high supply of operational energy (electricity).
Hexagonal Dynamic Façade (case study 14)	Demerit: • It is more aesthetically oriented than energy efficient.
Lighting smart façade (case study 15)	Merit: • Regulates natural light, makes shadow and blocks direct view from the outside.
Bio Façade (case study 16)	Merit: • Façade opens and closes automatically by responding to the changing environmental conditions.

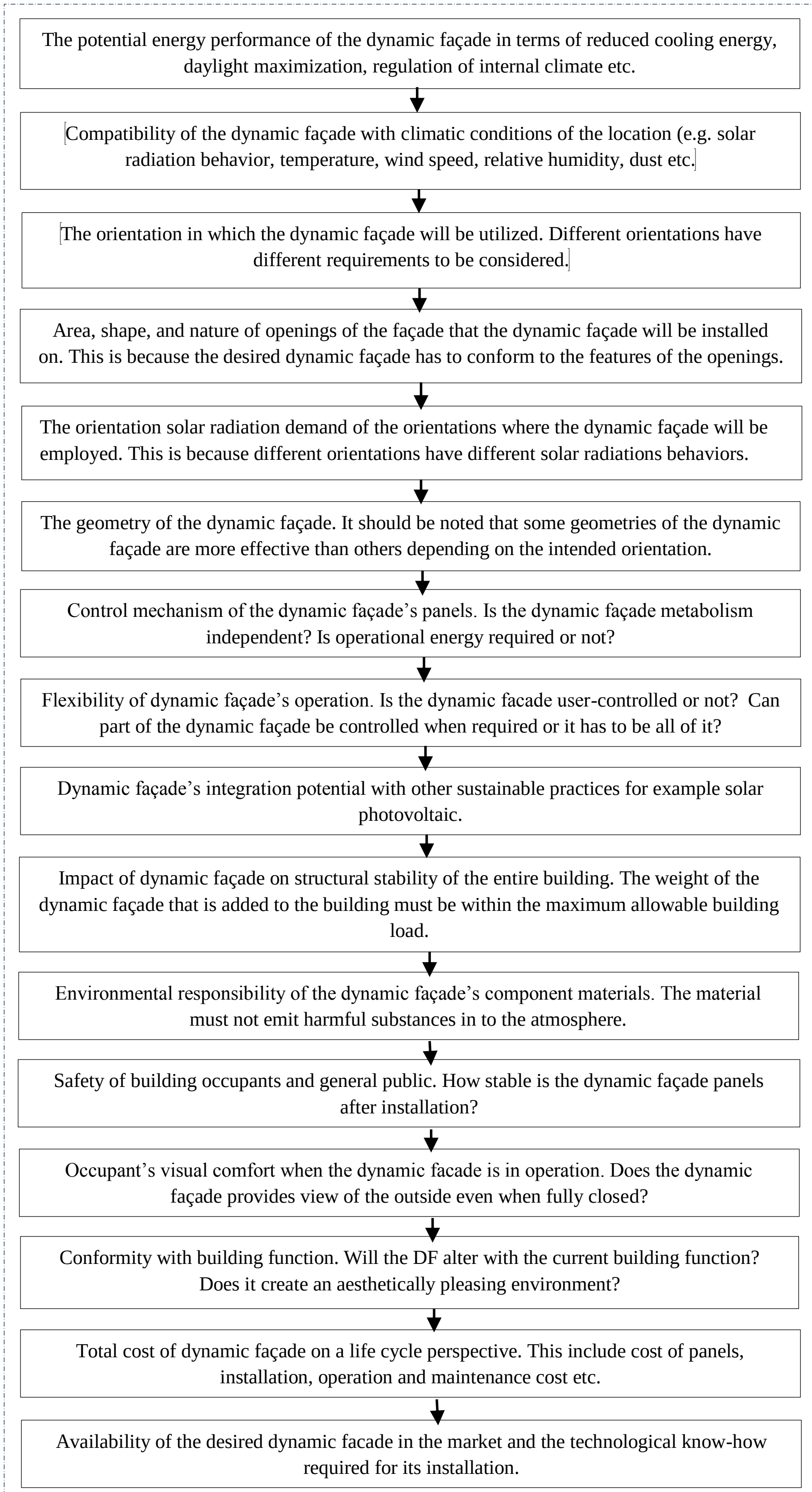
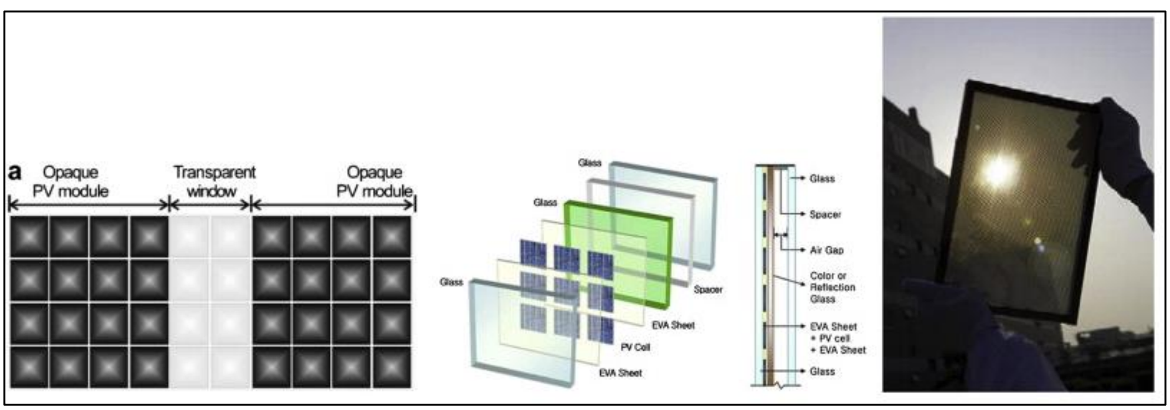


Figure 2.26 Guidelines regarding Dynamic Façade Design and Utilization.

Consequently, guidelines were developed to help architects and designers in making objective decisions in selecting, designing, and usage of dynamic facades. Guidelines regarding dynamic façade include all but not limited to that which is presented in Figure 2.26. The guidelines include factors regarding dynamic façade's design, cost, geometry, material sustainability, operation and control, occupants' safety, climatic conditions of the location, among other factors. Figure 2.26 presents guidelines regarding dynamic façade design and utilization.

2.4 Transparency of a BIPV and BIPV/T Panels

Solar cells are not usually transparent. Photovoltaic panels that consist of solar cells are usually completely opaque due to the influence of other laminated materials. However, numerous approaches by researchers seem to significantly increase the transparency of BIPV or BIPV/T panels. Yun et al. proposed that PV panels that are completely non-transparent can be placed side by side with glass panels used for lighting to create a façade as shown in Figure 2.27 (a).



(a) Yun et al. (b) Park et al. (c) Han et al.

Figure 2.27 Methods of increasing the transparency of BIPV or BIPV/T panels [31].

Similarly, Park et al. stresses that solar cells must not be closely packed during the process of welding. This is because the gaps between solar cells provide paths for sunlight irradiation as shown in Figure 2.27 (b). Alternatively, Han et al. proposed that thin film solar cell materials with a certain degree of transmittance can be used directly to form the façade as illustrated in Figure 2.27 (c) [31].

2.5 Importance of using CABS

The benefits of using dynamic facades over conventional static envelopes have been stressed from multi-dimensional perspectives by several researchers. In the area of energy efficiency optimization, CABS proved effective by saving total energy consumption significantly [23-24, 28, 105-106]. For instance, Baldinelli G realized an energy savings of 60kwh per year per each square metre upon comparing CABS with a non-responsive building shell [24]. Kasinalis C. et al obtained an improved indoor environmental quality conditions and 15-18% energy savings from a building with dynamic façade compared to the best performing static shell building [28]. Dynamic facades are also selective, (can either absorb, reject or reutilize) incoming solar heat and hence regarded as suitable tool for the attainment of nZEB [31, 33, and 105]. CABS also improve occupants' health as they involve using window glasses that block more ultraviolet and other unwanted rays from sunlight, thus, maximizing daylight utilization in buildings while improving the occupants' health conditions [106].

2.6 Cabs and Technology

The quest for improved energy efficient buildings has obliged various researches into dynamic windows' (facades) technology in an attempt to reach a lasting healthy solution [107]. Elizabeth A. K. et al. described recent advancements in electropolymeric display technology as an avenue to convey electroactive polymers to windows that are capable of achieving high levels of geometric and spectral selectivity through the building envelope. The authors went further to describe this technology as an opportunity to satisfy requirements such as the lighting, thermal and user requirements of occupied spaces [107].

Ruben B. et al. examined the technologies of electrochromic, gasochromic, liquid crystal and electrophoretic or suspended-particle devices and compared for dynamic daylight and solar energy control in buildings [108]. As of the time of the research (i.e. 2010), electrochromic windows were found to be most reliable and able to modulate the transmittance of up to 68% of the total solar spectrum [108]. However, the authors indicated that gasochromic windows were being developed and show promising results due to its simplicity in structure, and high transmittance modulation. However, the use of gas and a limited available number of cycles were considered as its shortcomings [108]. Figure 2.28 illustrates the Switching sequence of an electrochromic laminated glass [108].

Figure 2.28 Switching sequence of an electrochromic laminated glass [108].

Figure 2.29 The developed ACTRESS MFM prototype [105].

Another concept of multifunctional façade module (MFM) called ACTRESS (i.e. ACTive RESponsive and Solar) was conceived and a prototype was developed by Fabio F et al. as an advancement of advance integrated facades (AIFs) [105]. The prototype was tested in a winter season where heating was the main requirement [105]. Figure 2.29 shows the developed ACTRESS MFM prototype (opaque sub module and transparent sub module) [105]. The ACTRESS façade module was constructed to overcome limitations experienced by the current AIFs [105]. Most notably, the design criteria considered architectural aesthetical values and engineering issues from start to finish [105]. The measurement apparatus constituted a number of 68 sensors connected to a data logger measuring relevant physical quantities (such as temperatures, heat fluxes and irradiances) that influence the thermos energetic behaviour of the modules [105]. Schematic diagram of these apparatuses are shown in Figure 2.30 [105].

Machi Zawidzki introduced polarized film shading system (PFSS) as an alternative approach to cellular automaton shading system (CASS) for building facades [109].

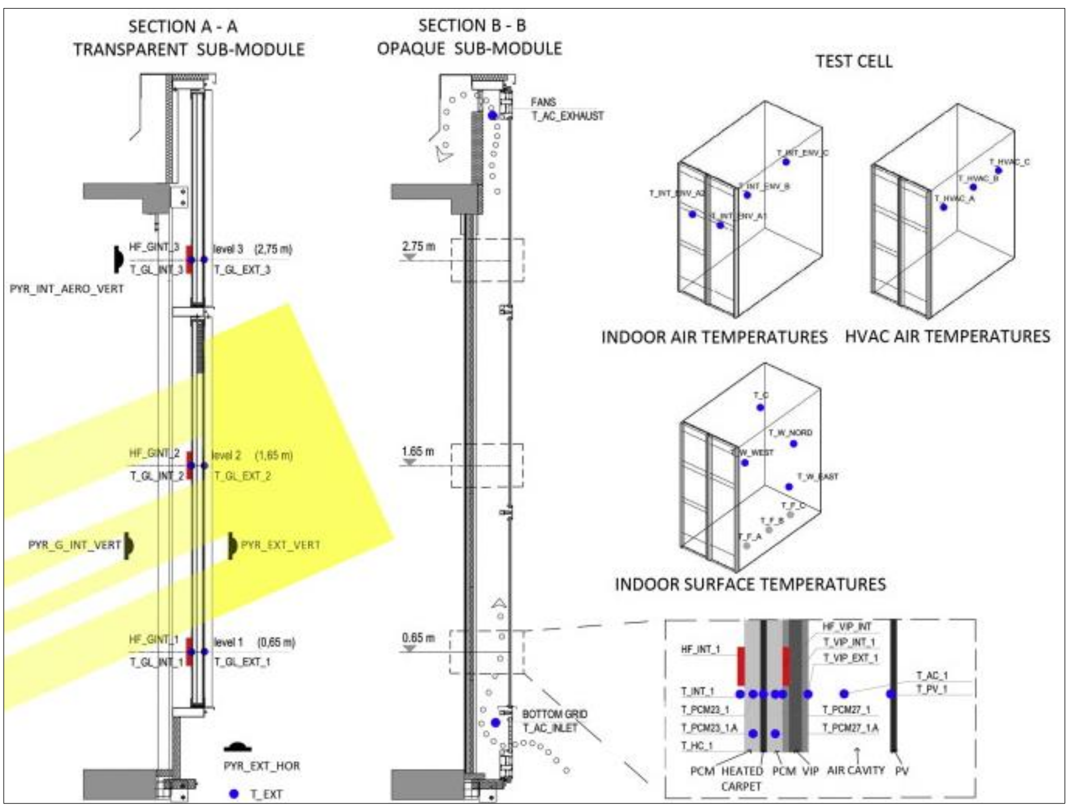


Figure 2.30 Scheme of the experimental apparatus (pyranometers PYR, thermocouples, T, heat flux metres HF) [105].

The later was based on rectangular array of cells and used liquid crystal technology while PFSS is based on opto-mechanical modules whose opacity is a function of the rotation of polarized film elements [109]. Zawidzki examined PFSS in regular tessellations: triangular, square and hexagonal and went ahead to visualize the simulation of each of these regular tessellations [109].At the end, Machi Zawidzki concluded that a concept of rotating polarized film elements that are arranged in regular tessellation is simpler, low-maintenance, and is potentially more robust and affordable compared to the existing systems for dynamic control of building envelopes [109].

2.7 Dynamic Facades and Future Challenges

Francesco G. et al. Proposed that future research in dynamic façade optimization should explore the influence of each climate (other than temperate oceanic climate) on the ideal WWR and give recommendations for façade design of energy efficient office buildings in different climatic conditions [110]. Better energy efficient buildings will be significantly improved by providing solutions to conceptual barriers separating the design of architectural facades and from the simulation of the environmental performance [111]. Bakker L.G. et al. proposed a future research with more user-friendly interfaces that will ease the hardship of manual interventions [28]. Also, further research is required in order to examine how various technologies can be integrated with optimized energy saving performance in the field of smart windows [30]. Kacinalis C. et al. equally suggested that future research should address the challenge of simplifying the adaptive actions associated with dynamic facades with little or no compromise in performance [27].

Having conducted a comprehensive review on solar facades, Loonen R.C.G.M. et al. indicated that for effective contributions to be made, it is necessary that emerging techniques are deployed on a wide scale with competitive cost-benefit ratios [21].

2.8 Challenges of Modelling and Simulating Dynamic Facades

Modelling and simulating dynamic facades using current Building Simulation Programs (BSPs) present series of challenges. This is because today's BSPs are ideal for static facades. Loonen and Hensen [112] focus on consideration regarding the optimizations of dynamic façade. Nevertheless, it can be inferred that modelling and simulation of dynamic facades entails the following challenges [112].

- Determining the sequence (i.e. time series) of dynamic façade properties over time.
- How to indicate that façade properties change with time during the simulation run-time to properly account for transient heat transfer energy storage effects.
- Determining how to model the operation of the façade based on adaptation [112].

Similarly, Loonen et al. [113] stated that another challenge lies in the difficulty in capturing all the heat transfer phenomena during Responsive Building Element (RBE) state transitions [113]. Loonen et al. [113] attributed the difficulty in modelling dynamic facades to the following three reasons:

- Limited flexibility of Graphical User Interface (GUI) to accommodate the changeable properties of RBEs.

- Lack of flexibility regarding the solution routines for energy balance equations. This is because most of the methods for solving the differential equations in Building Energy Simulation (BES) tools are only capable of working with time-invariant parameters.
- Unsophisticated control strategies in most of the BES tools with limited range of sensor and actuator options.
- Reliance on approximations or simplifications in predicting the performance of RBEs [113].

Michael Wetter [114] described the inability of most building simulation programs to model the dynamics of HVAC systems as another challenge. This makes it difficult to model many standard control sequences such as those described by ASHRAE [2006] and CIBSE [2000] [114]. Also, lack of higher level of abstraction and modularization to manage the increased complexity of dynamic facades compared to what is used in current BSPs [115].

2.9 Building Energy Simulating (BES) Tools

Numerous BES programs have been developed and enhanced within the past 6 decades [116]. These programs are widely used throughout the building energy community [116]. D. B. Crawley et al [116] conducted a comparison analysis on the capabilities of 20 main building energy simulation programs based on the information obtained from the developers. The information obtained covers modelling capability of the software, simplicity of usage, accuracy, result interpretation, cost among other things [116].The building energy simulation programs that were considered in the comparative study are BLAST, BSim, DeST, DOE-2.1E , ECOTECT, Ener-Win, Energy Express, Energy-10, Energy Plus, eQUEST, ESP-r, HAP, HEED, IDA, IES /VES, Power Domus, SUNREL, Tas, TRACE and TRNSYS.

Attia et al. [117] compared 10 BPS tools based on online survey where 249 valid responses were obtained. The tools considered were Energy 10, Design Builder, DOE-2, ECOTECT, Green Building Studio, HEED, IES VE, eQUEST, Energy Plus and Energy Plus-SketchUp Plugin (OpenStudio). Usability and Information Management (UIM) of interface and (2) the

Integration of Intelligent design Knowledge-Base (IIKB) were the 2 factors considered for identifying a building simulation program as "*Architect Friendly*". It was observed that at least 22% of the respondents use *DesignBuilder*. *DesignBuilder* was also considered as a tool that is used in early design phase by the respondents. The tools were grouped into three categories and results revealed that *DesignBuilder* was ranked in the second category with a slightly less agreement among the respondents for architect-friendliness even though it was popularly known to have friendly GUI and varied graphical output features. Highest numbers of responses were obtained from architects and designers and many were from LEED accredited professionals [117]. A summary of the selection criteria of BPS tools based on architects‟ and engineers‟ perspective of the requirements of the tool was presented in a research publication (Attia et al., 2011).

Xin Zhou et al. compared 3 building energy modelling programs regarding HVAC systems [118]. The programs were EnergyPlus, DeST and DOE-2.1E. The 3 programs

	Energy Plus	ESP-r	IDA ICE	IES	TRNSYS
Simulation Solution					
Simulation of loads, systems and solutions	X	X	X	X	X
Iterative solution of nonlinear systems	X	X	X	X	X
Duration of Time Calculation					
Variable time intervals per zone for interaction of the HVAC system	X	X			
Simultaneous selection of building systems and user		X	X	X	X
Dynamic variables based in transient solutions	X	X	X		
Complete Geometric Description					
Walls, roofs and floors	X	X	X	X	X
Windows, skylights, doors and external coatings	X	X	X	X	X
Polygons with many faces	X	X	X	X	
Imports of building from CAD programs	X	X	X	X	X
Export Geometry of Buildings for CAD software	X	X	X		
Import / Export of simulation models of programs	X	X	X	X	
Calculation of thermal balance	X	X	X	X	X
Absorption / release of moisture from the building materials	X		X	X	X
Internal thermal mass	X	X	X	X	X
Human thermal comfort	X	X	X	X	X
Solar Analysis	X				X
Analysis of isolation	X	X	X	X	X
Advanced fenestration	X	X	X	X	X
Calculations of the building in general	X	X		X	X
Surface temperatures of zones	X	X	X	X	X
Airflow through the windows	X	X		X	X
Driving surfaces	X	X	X	X	X
Heat transfer from the soil	X	X	X	X	X
Thermophysical variable			X		
Daylighting and lighting controls	X	X	X	X	
Infiltration of a zone	X	X	X	X	X
Automatic calculation of coefficients of wind pressure				X	
Natural Ventilation	X	X	X		X
Natural and mechanical ventilation				X	X
Control open of windows for natural ventilation	X	X	X		X
Air leaks in multiple zones	X	X	X		X
Renewable Energy Systems					
Solar Energy	X	X		X	X
Trombe Wall	X	X	X	X	X
Photovoltaic panels	X	X		X	X
Hydrogen Systems		X			X
Wind Energy		X			X
Electrical Systems and Equipment					
Energy Production through R.E.	X	X			X
Distribution and management of electric power loads	X	X			X
Electricity generators	X				X
Network connection	X	X			X
HVAC Systems					
HVAC idealized	X	X	X	X	X
Possible configuration of HVAC systems	X	X	X	X	X
Repetitions cycle air	X	X	X	X	X
distribution systems	X	X	X	X	X
Modeling CO_2			X	X	X
Each distribution of air per area	X	X	X	X	X
Forced air unit per zone	X	X	X	X	X
Equipment Unit	X	X		X	X

Figure 2.31 Comparison of Features of Various Simulation Software tools [98].

were found to have fundamental capabilities and appropriate modelling assumptions for HVAC systems calculations. However, it was found that EnergyPlus has more comprehensive component models than DeST and DOE-2.1 [118]. Similarly, Joana Sousa reviewed and compared 5 simulation tools in an attempt to enable designers make informed decisions [119]. The 5 Energy Simulation Software tools compared were: Energy Plus, ESP-r, IDA ICE, IES VE and TRNSYS. EnergyPlus satisfied most of the comparison criteria as presented in Figure 2.31 and is considered to be more powerful than BLAST and DOE. It should be noted that, where EnergyPlus is used, *DesignBuilder* needs to be used for the simulation [119]. A. S. Mahmoud tabulates a summary of the features of software tools where *DesignBuilder* exhibits distinguished qualities [120]. The most important consideration in the selection of a building simulation tool is the ability of the tool to satisfy the user's requirements. Having examined the major building simulation tools, it is found that most of programs do not possess the capability of modelling a climate responsive building envelope. In addition, the availability of the program is a thing of concern. So far *DesignBuilder* v4.5 satisfies these requirements and is within reach.

2.10 *DesignBuilder* Capabilities (V4.8)

DesignBuilder is a tool used in early design phase of a project. It provides a friendly GUI to today's widely used energy simulation engine – EnergyPlus - and is popularly known to have varied graphical output features. The strengths, weaknesses and data exchange capabilities of *DesignBuilder* illustrated that the simulation program had most comprehensive user-interface for the most widely used energy simulation engine EnergyPlus.

The capabilities of *DesignBuilder* are summarized below:

- Innovative productivity features for rapid modelling: an easy to learn and fast to use 3-D modeller.
- Fully-featured optimization and cost-benefit analysis: multi-criteria optimization to help meet design goals.
- Simulation made easy: EnergyPlus simulations for energy and comfort analyses.
- Allows importation of BIM models from Revit and Sketchup etc
- Accurately assess natural daylight and visual comfort: Reports daylight factors and illuminance using Radiance.
- Accesses EnergyPlus advanced HVAC modelling: A powerful and flexible interface to EnergyPlus HVAC.
- Calculate and view airflow and 3-D temperature distribution: CFD calculates distribution of air properties in and around buildings.
- Stunning rendered images and site shading analysis: rotate, zoom and walkthrough the designed building.
- Allows for the integration of BIPV system.

2.11 Summary of Findings

The literature review revealed that world energy concerns and climate crises have necessitate new ideas and investments in energy efficient strategies in the building industry. The building sector is consumes over 40% of overall primary energy consumption across the globe and nearly up to 30% of the world's total Carbon Dioxide (CO_2) emissions. In KSA, the building sector, which includes residential and commercial buildings consume 50% and 15% respectively. An aggregate that accounts for 65% of the total electricity generated in the country. An analysis conducted by SEC indicated that air conditioning systems in buildings across Saudi Arabia account for nearly 70% of total energy consumed in buildings. On the other hand, only 22% and 21% of total energy consumption in buildings is consumed by air conditioning in the United Kingdom and the United States respectively.

Previous studies were reviewed in order to identify energy conservation measures that could help reduce the HVAC system energy consumption in buildings. Various Energy Conservation Measures have been identified and presented. An in-depth study on different dynamic facades and their respective classifications provide sufficient knowledge on the subject matter. 16 case studies of built examples of dynamic facades have been conducted. The findings of the case studies is summarised and presented in a tabular form to serve as checklist for selection of dynamic façade.

In order to appreciate the benefits of dynamic facades, an assessment of using Climate Adaptive Building Shells (CABS) has been compared to conventional static façade. Also, developing technologies related to CABS have been brainstormed alongside future challenges of dynamic facades.

Series of challenges regarding modelling and simulating dynamic facades have been presented. Finally, a comparative analysis on Building Energy Simulation (BES) tools has been conducted to justify the selection of *DesignBuilder*. *DesignBuilder* capabilities conclude the literature review.

CHAPTER 3

MODEL DEVELOPMENT

This chapter describes the procedures conducted in modelling the 2 base case buildings and dynamic facades utilized in this research. A theoretical base case (TBC) and a real base case (RBC) office buildings were developed. 2 dynamic facade models were developed and their energy performances examined on the TBC and the RBC respectively.

3.1 Development of Dynamic Façade Model

There is a limitation in the capability of energy analysis tools to model and simulate a dynamic façade. The current energy analysis tools were designed to model and simulate buildings with ordinary (static) facades. Although *DesignBuilder* possesses the capability of manipulating and mimicking the properties of a dynamic façade during calibration, it is almost impossible to model the intended responsive façade in *DesignBuilder* environment. This is due to the usual complex geometry of a dynamic façade and the rigidity of *DesignBuilder* when it comes to modelling such. Modelling a dynamic façade requires highest level of flexibility. As such, it became mandatory to search for alternative solution. A search for a means of modelling a dynamic façade from the available modelling tools. After thumbing through numerous modelling tools, *Sketchup* emerged the most viable option. This was due to its modelling flexibility and integration potential with other available tools including *DesignBuilder*. A researcher can model almost any geometric shape irrespective of its complexity in *Sketchup*. *Gmodeller* is a *sketchup* plugin that integrates *sketchup* with *DesignBuilder* which makes the task possible. It allows the user to transfer models from *sketchup* to *DesignBuilder* conveniently. The user can then calibrate the geometry to the required specifications in *DesignBulder* and examine their impact on energy savings.

3.1.1 Dynamic Façade Modelling

Modelling the required dynamic façade involves selecting the appropriate building envelop. A façade that mimics the geometry and operation module of *Dynamic Honeycomb Façade of Al-Bahr* was selected. This was due to the simplicity in controlling and monitoring of the façade's transparency at various times of the day. Also, it was easy and practical to examine the energy saving of the façade throughout the day. Added to its aesthetical appearances, the façade was considered appropriate for this research.

Proper façade modelling involved careful observation of all vital information regarding its operation, positioning and characteristics. Special attention was paid to the height of individual panels, panel's distance away from the exterior walls and nature of façade's opening. For easy analysis, the façade's mode of operation (transparency) was assumed to be in 5 phases. These phases were: 0%, 20%, 45%, 70%, and 85% transparencies. Thus, when the façade is fully opened, only 85% transparency is achieved. The component material of the façade covers at least 15% which results to a maximum of 85% transparency. Using *gmodeller* in *sketchup*, a single panel was designed for each of the above 5 phases of the façade's transparency. Each panel was then copied, mirrored, and arranged to cover the desired area. Subsequently, the modelled façade was imported to *DesignBuilder* as a *3-dimensional* model. Figure 3.1 (a-b) respectively illustrate front and side views of the developed and imported dynamic façade model and their transparencies.

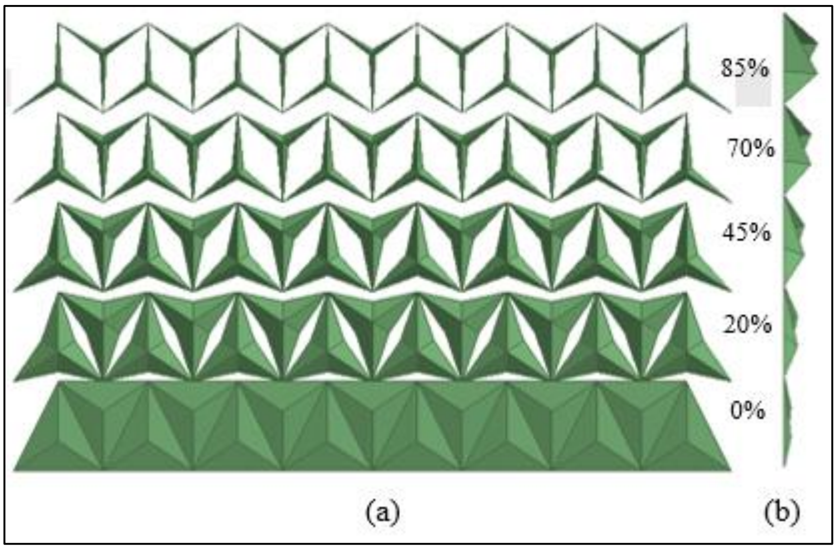


Figure 3.1 Views of Developed Dynamic Model

3.1.2 Development of a Sample Block to Investigate the Developed Model

The energy saving potential of the developed dynamic model must be carefully and accurately examined. In this regard, an office with a square plan and elevation was developed for the investigation. The office's service zone was centrally located. This divides the building plan into 4 equal zones excluding the service (central) zone. The 4 zones were Z_East, Z_South, Z_West, and Z_North. The above 4 zones represented the east, south, west, and north facing façade of the building. All the 4 zones had equal

WWR that was subjected to the incoming solar radiation. Figure 3.2 illustrates the building floor plan.

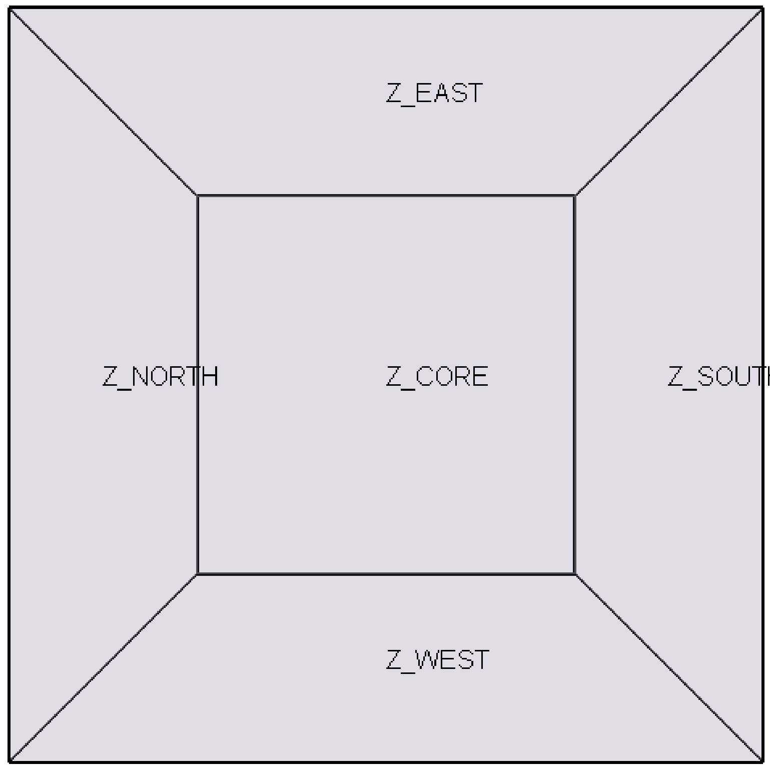
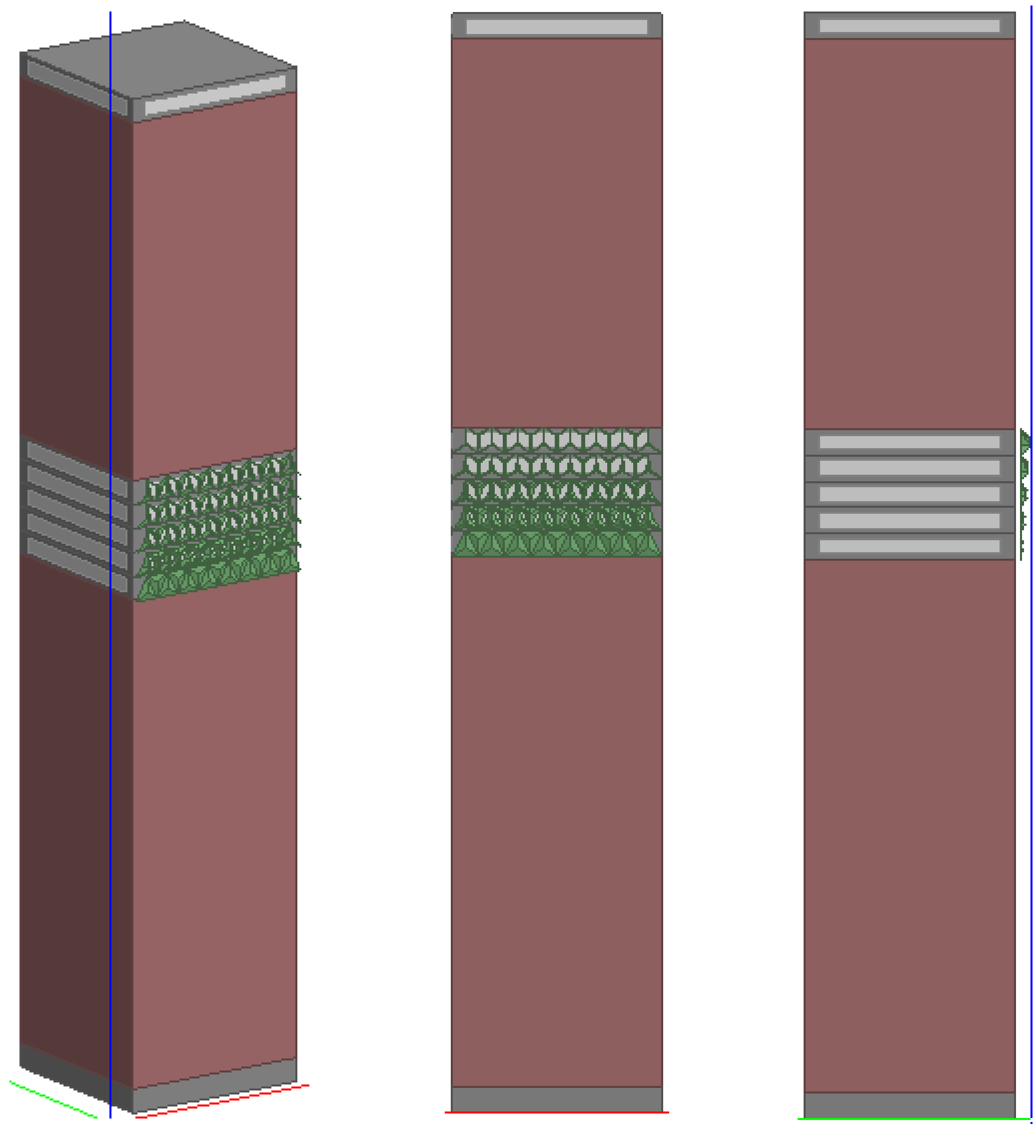


Figure 3.2 Office Building Plan

The sample office was divided in to 5 parts in height. Namely: ground floor; lower component block; the target zone (7th, 8th, 9th, 10th, and 11th floors); the upper component block; and the roof. The developed model was examined on all 5 floors of the target zone. Each of the 5 floors was covered by 1 of the phases of the model's transparency. The model was positioned at a distance of 1 m away from the building. The target zone was intentionally positioned half-way along the building height. This was to avoid or minimize errors due to re-radiated solar rays from the ground and adjacent objects, and to avoid the impact of roof in blocking or reducing the effect of the solar rays. Figure 3.3 (a-c) show views of the dynamic model on the developed office building.



(a) (b) (c)

Figure 3.3 Views of Dynamic model on the Sample Office Building.

3.1.3 Building Calibration and Simulation

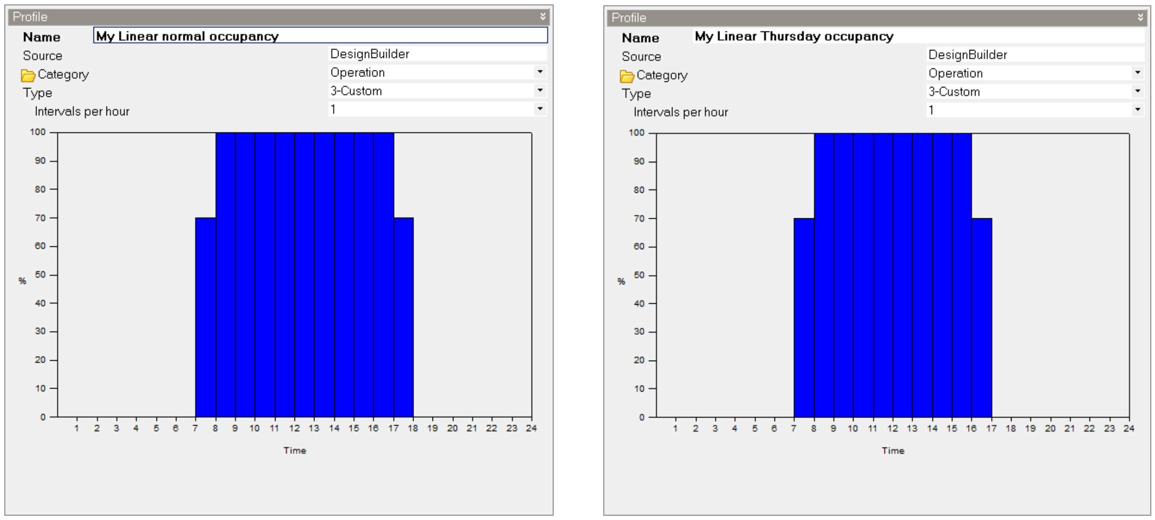
Building calibration was conducted at both site and building level as usual. Data was then specified in both program and model options. This determines the nature of the specifications that were provided throughout the calibration exercise. Data was equally specified under *activity*, *construction*, *lighting*, and *HVAC* sub-fields. Calibration for the imported shading elements was carried out at the building level. Specified data were *material*, *transparency*, and *operation schedule* of the shading elements. Simulations were conducted at various stages of the exercise. Investigations were carried out and presented in Chapter 5. Key areas of the model are explained in details below:

Site Level

At site level, the region was set to Saudi Arabia and King Khalid International Airport template was selected. SAU-RIYADH IWEC was chosen as the hourly simulation weather data. Sunday was also assigned to mark the beginning of the week.

Building Level

Activity Tab: Generic office area template was selected as it corresponds with the nature of the building under investigation. *DesignBuilder* calculates density (people/m^2) as 0.11 and occupancy schedules were then assigned. The occupancy schedules describe the nature of the offfice's operation for various days of the week. Figure 3.4 (a-b) illustrate the attached schedule. A total of 30 days were calculated as *Holidays per year*. Holidays that made up the list are Eid-ul-Fitr (10 days), Eid-ul-Adha (10 days), National holiday (2 days) and Ramadhaan compensation for the number of working hours missed during the month of Ramadhaan (8 days). Figure 3.5 tabulates the name, start date, and number of days for the holidays.



(a) Normal day occupancy schedule (b) Thursday occupancy schedule

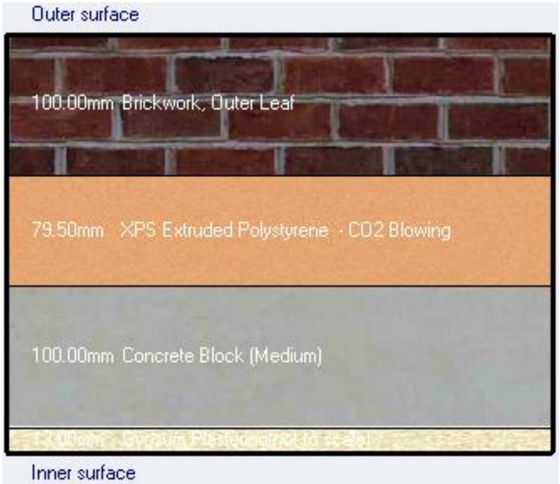
Figure 3.4 Occupancy schedules

Name	Start date	Number of days
Eid-ul-Fitr	7 July	10
Eid-ul-Adha	15 September	10
National holiday	September 22	2
Ramadhaan Compensation	April 22	8

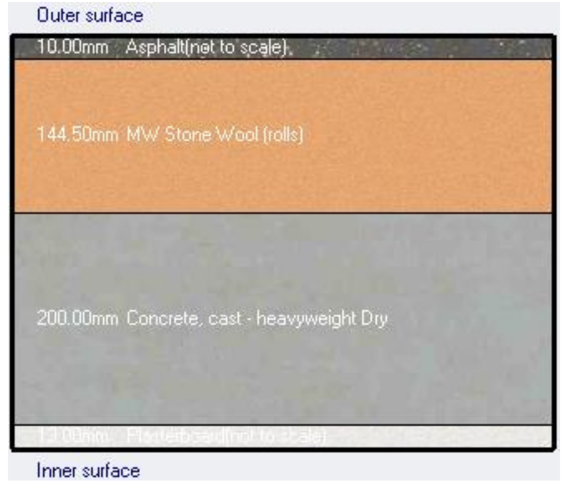
Figure 3.5 Holidays per year

Other specified information include *Cooling Setpoint Temperature* of 23^{0}C, *Minimum Fresh air* (5 l/s-person), *target illuminance* (500 lux), *computers* and *equipment gain* (5 W/m^2) each.

Construction tab: Best practice, medium weight was set as the construction template. Project wall, project flat roof, and project ground floor were selected and modified as external walls, flat roof, and ground floor respectively.



(a)



(b)

(c)

(a) Wall cross section. (b) Roof cross section. (c) Floor cross section.

Figure 3.6 Wall, Roof, and Floor cross sections.

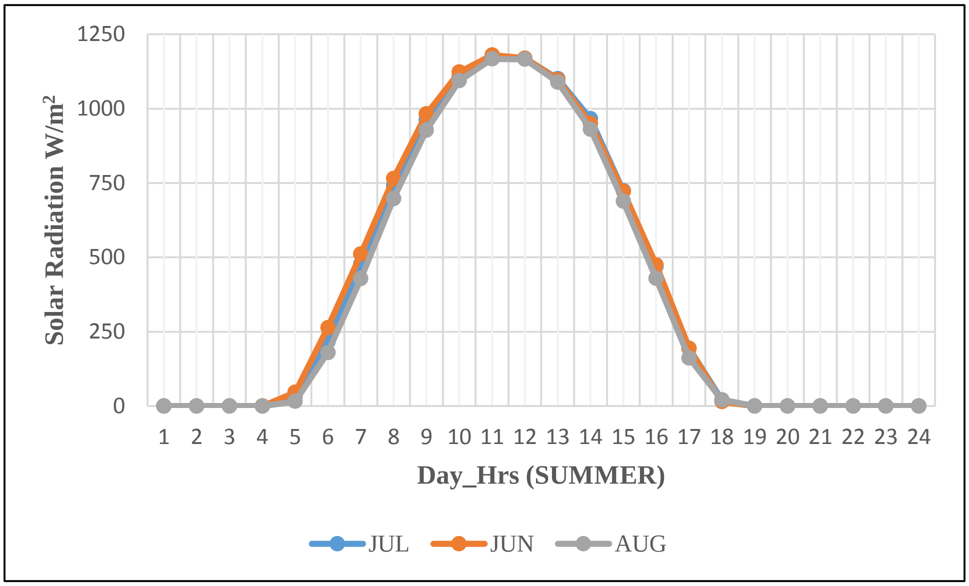
Figure 3.6 (a-c) illustrate cross sectional views of the modelled layers.

Polyvinylchloride (PVC) – tiles was selected as the component block material and a transmittance schedule was subsequently attached. Various steps undertaken in order to develop the schedule for the modelled dynamic facades are described below:

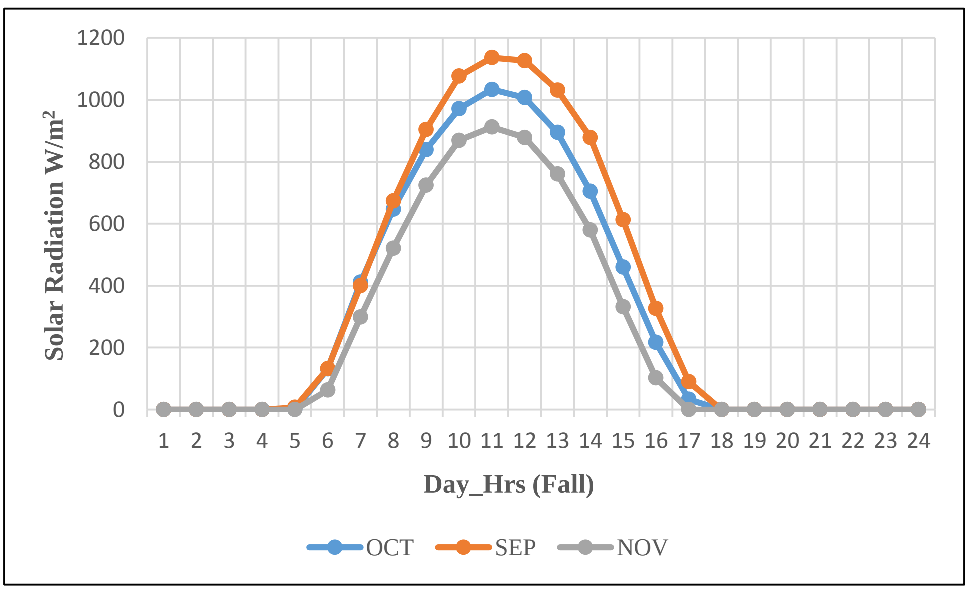
Step 1: The year was divided into 4 seasons to represent summer, fall, winter, and spring. Each season was assumed to constitute 3 months. That is, summer constitute June, July, and August whereas September, October, and November form fall. Winter comprises December, January, and February while spring consists of March, April, and May.

Step 2: *Climate Consultant tool* was employed to obtain the maximum solar radiation (W/m^2) for each month of the year for the location of Riyadh. After categorizing the months into seasons, the month with the highest solar radiation was regarded the worst case and hence chosen as sample months for respective seasons. June, September, February, and May emerged as sample months for summer, fall, winter, and spring respectively. Among the seasons, the maximum and minimum solar radiations were recorded in June (summer) and February (winter) respectively. Figure 3.7 (a-d) show graphical representation of seasonal solar radiation (W/m_2) for all the months of the year as obtained from the tool.

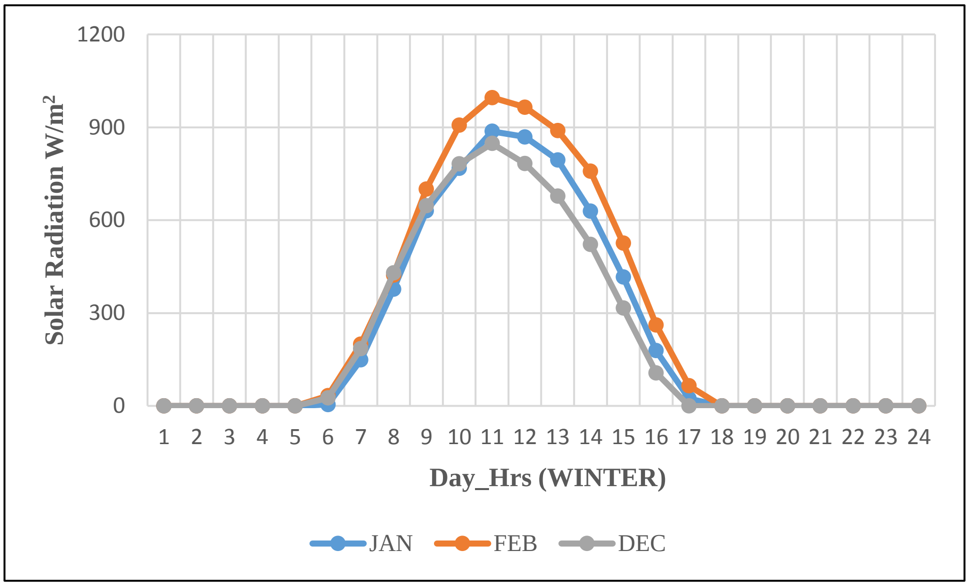
Step 3: 4 schedules were then developed for each of the seasons based on the worst case obtained from step 2 above. The schedules were developed to have 5 steps with each step representing a certain percentage of transparency developed for the dynamic façade. Figure 3.8 (a-d) present the 4 schedules for summer, winter, fall, and spring respectively.



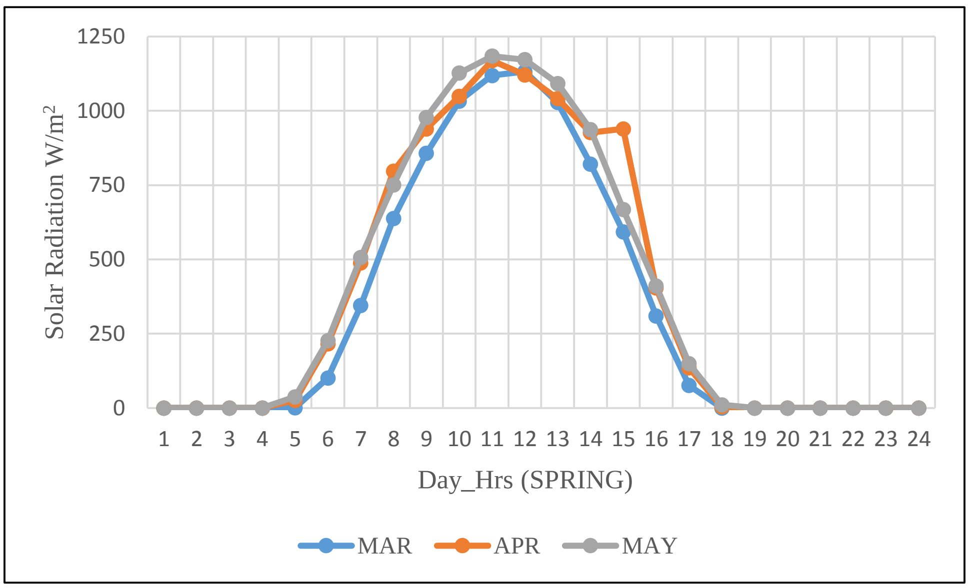
(a) Summer solar radiation (W/m^2)



(b) Fall solar radiation (W/m^2)

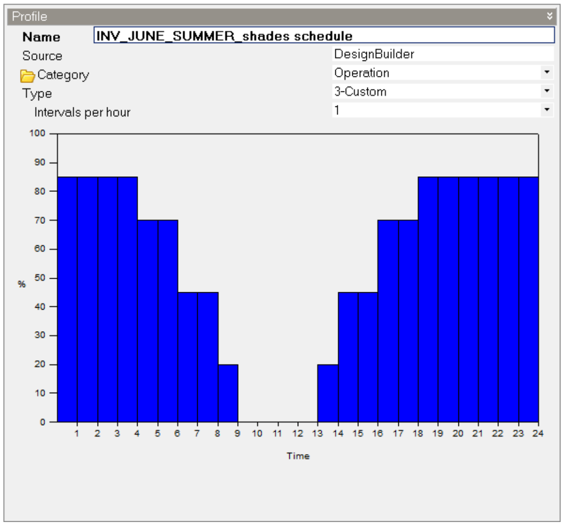


(c) Winter solar radiation (W/m^2)

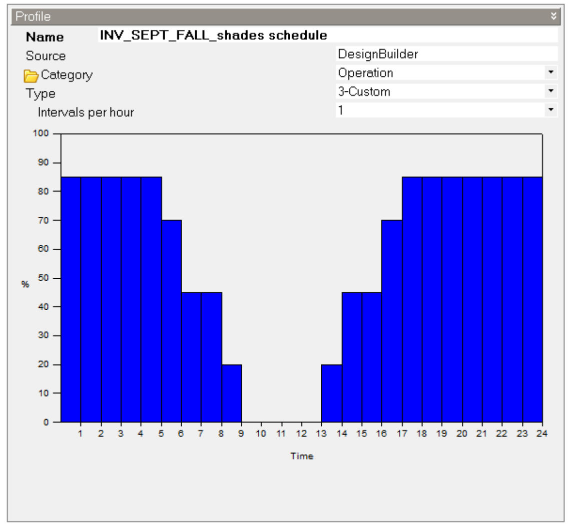


(d) Spring solar radiation (W/m^2)

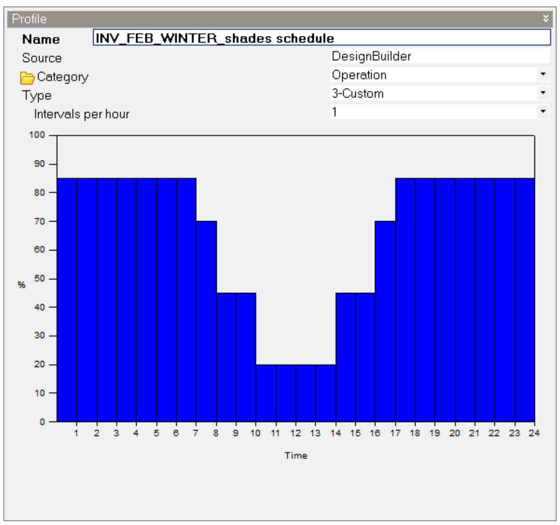
Figure 3.7 Seasonal Solar Radiations



(a)



(b)



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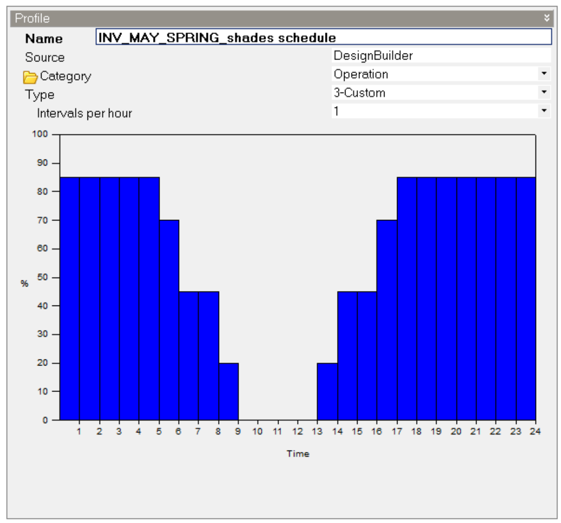
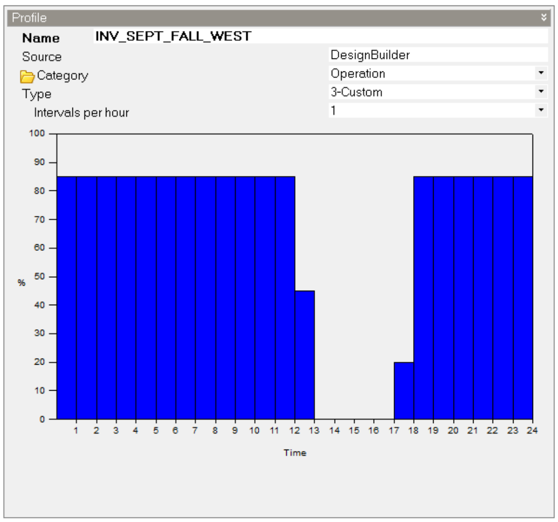


(d)

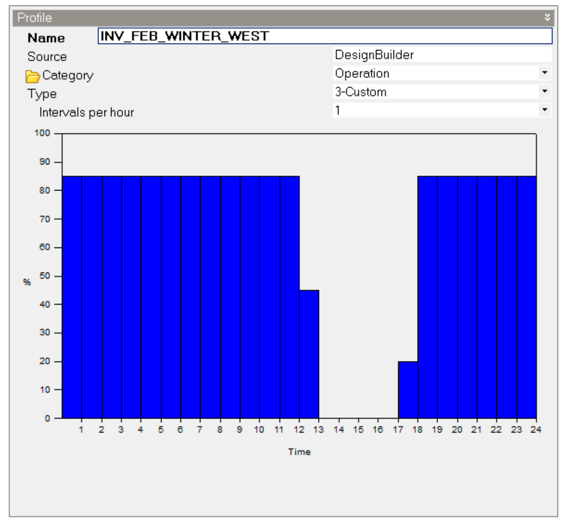
(a) Summer transparency schedule. (b) Fall transparency schedule. (c) Winter transparency schedule. (d) Spring transparency schedule.

Figure 3.8 Seasonal transparency schedules.

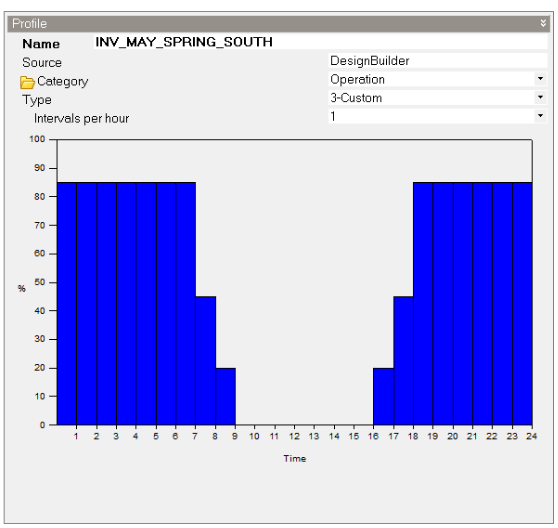
However, these schedules only satisfy seasonal requirements alone. For effective performance of dynamic shades, the schedules were tailored to also satisfy orientation requirements at the same time. Figure 3.9 (a & b) presents fall and winter operation schedules on the West orientation while Figure 3.9 (c & d) depict spring and summer operation schedules on the South orientation. Figure 3.9 is an example of dynamic façade orientation schedule that satisfy both seasonal and orientation solar demands.



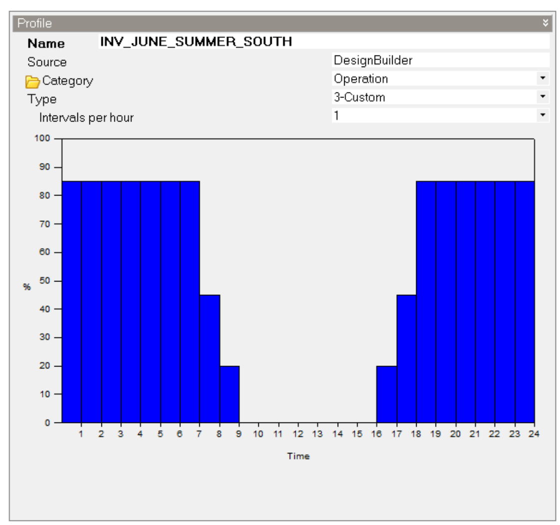
(a) Fall schedule on the West orientation



(b) Winter schedule on the West orientation



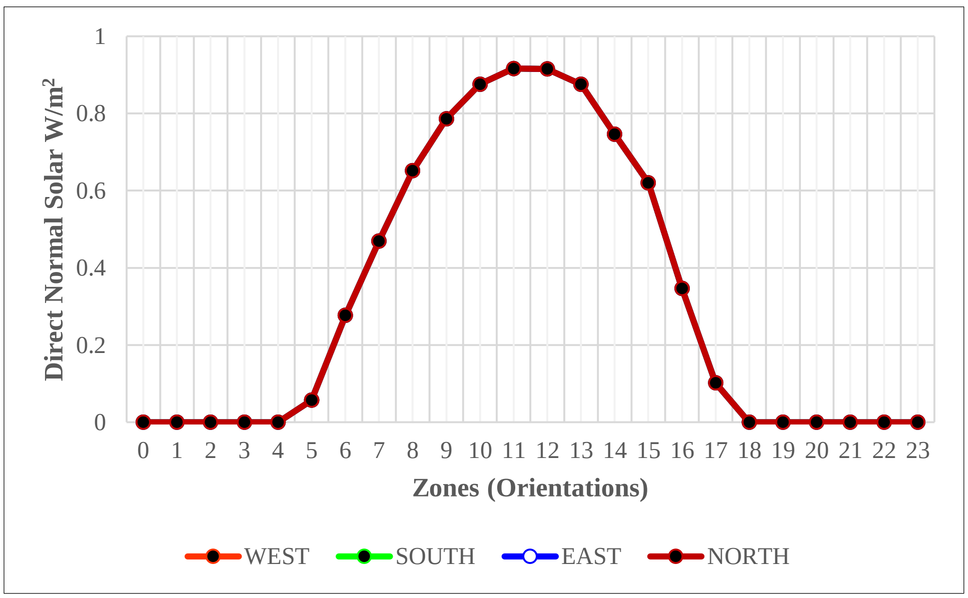
(c) Spring Schedule on the South Orientation



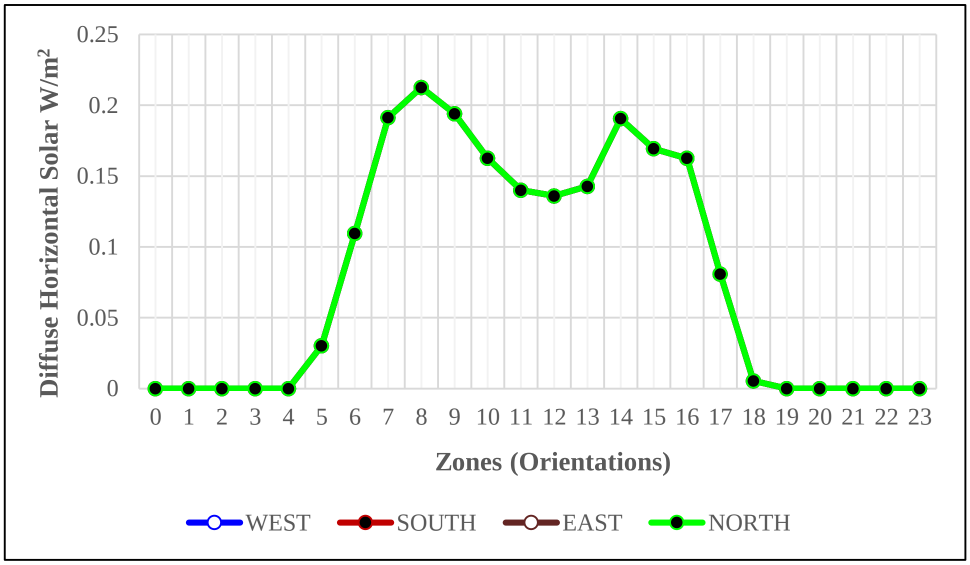
(d) Summer schedule on the South Orientation

Figure 3.9 Seasonal and orientation sensitive transparency schedules.

It is worth indicating here that these schedules were not developed based on either direct or diffuse solar radiation types. Rather, the schedules were developed based on solar heat gain that reaches the zones of the building in form of SGEW in *DesignBuilder*. This is because both direct and diffuse solar radiations for any given day are not orientation dependent. That is, the direct solar radiations are the same irrespective of the zone or orientation of the building. The same also applies for diffuse solar radiations. In that case, solar heat gain obtained as SGEW within the zones was the most reliable means in which the schedules based upon. Figure 3.10 (a, b) illustrate direct normal and diffuse horizontal solar radiations respectively. Figure 3.11 shows SGEW on all the zones which was used to develop the operation schedules.



(a) Direct Normal Solar W/m^2



(b) Diffuse Horizontal Solar W/m^2

Figure 3.10 Direct Normal and Diffuse Solar Radiations W/m^2

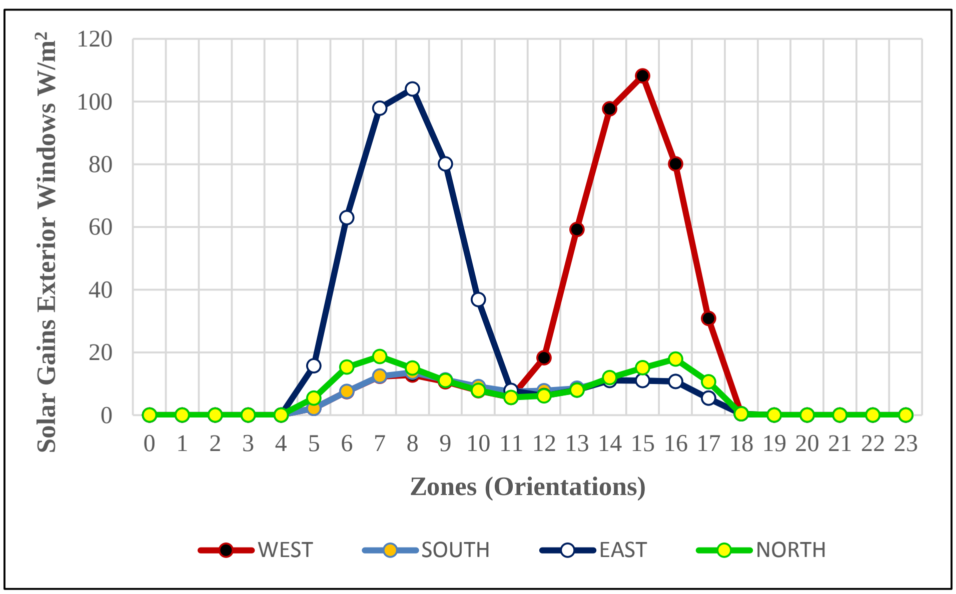
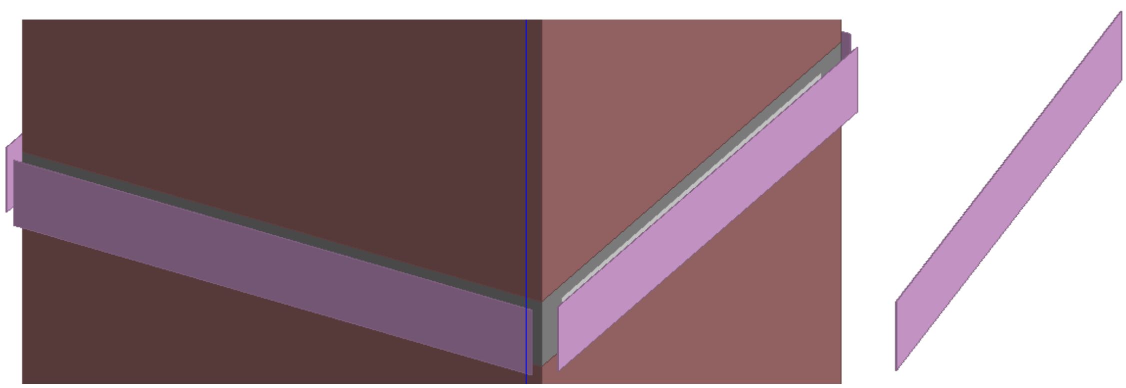


Figure 3.11 Solar Gains Exterior Windows W/m^2

In order to appreciate the impact of dynamic façade on the office building, a solid screen shading device 3 cm thick was equally developed. The solid screen shading device (static) remains in place throughout the day (24/7) all the time. The same properties were given to both the dynamic and solid screen shading devices for the purpose of comparison when it comes to the impact of geometry. Figure 3.12 (a-c) illustrate views of the solid screen (static) shading device.

Openings tab: Double glazing, clear, no shading is commonly utilized in office buildings across KSA. As such, the same was selected as *glazing template*. Dbl Clr 6mm/13mm Air formed the glazing type of the external windows. Dimensions type was *none* as windows were manually drawn to the desired dimensions. The window covered an area of 66.72 m2 on each orientation with 27.8m * 2.4m as dimensions.

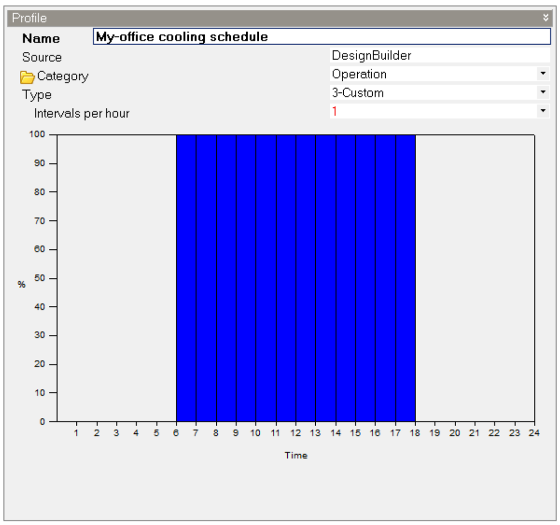


(a) (b)

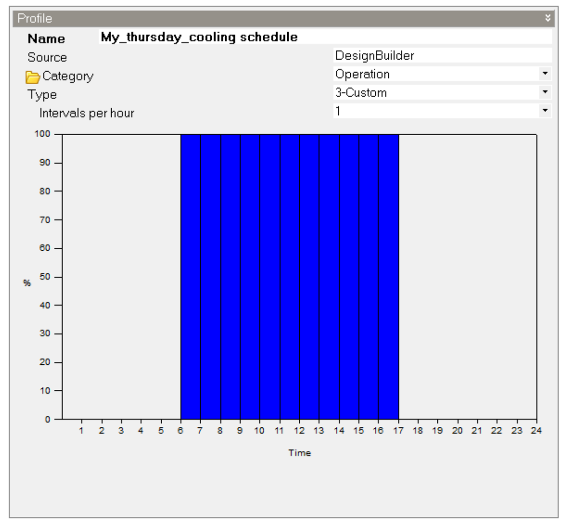
Figure 3.12 Solid screen shading device

Lighting tab: *Best practice* was selected as lighting template. Recessed luminaire type formed the general lighting. Lighting control was provided and the control type was set to linear. 30% and 70% was the percentage zone covered by lighting area 1 and 2 respectively.

HVAC tab: Based on previous investigations on the performance of different HVAC systems, *VAV, Air-cooled Chiller, HR, Outdoor air reset + mixed mode* was selected as HVAC template. Cooling is provided 2 hours and 1 hour before and after occupancy respectively. Figure 3.13 shows cooling schedule. It should be noted that heating and domestic hot water have not been provided.



(a) Normal day cooling schedule.



(b) Thursday cooling schedule.

Figure 3.13 Cooling Schedules.

3.1.4 How to Model a Dynamic Façade and Examine its Impact on Energy Saving Potential

A flow chart is developed which summarizes a detailed procedure involved in modelling a dynamic façade in *DesignBuilder*. The flow chart also demonstrates how to examine the impact of a dynamic façade over other alternatives with regards to energy saving potential. Figure 3.14 illustrates the flow chart.

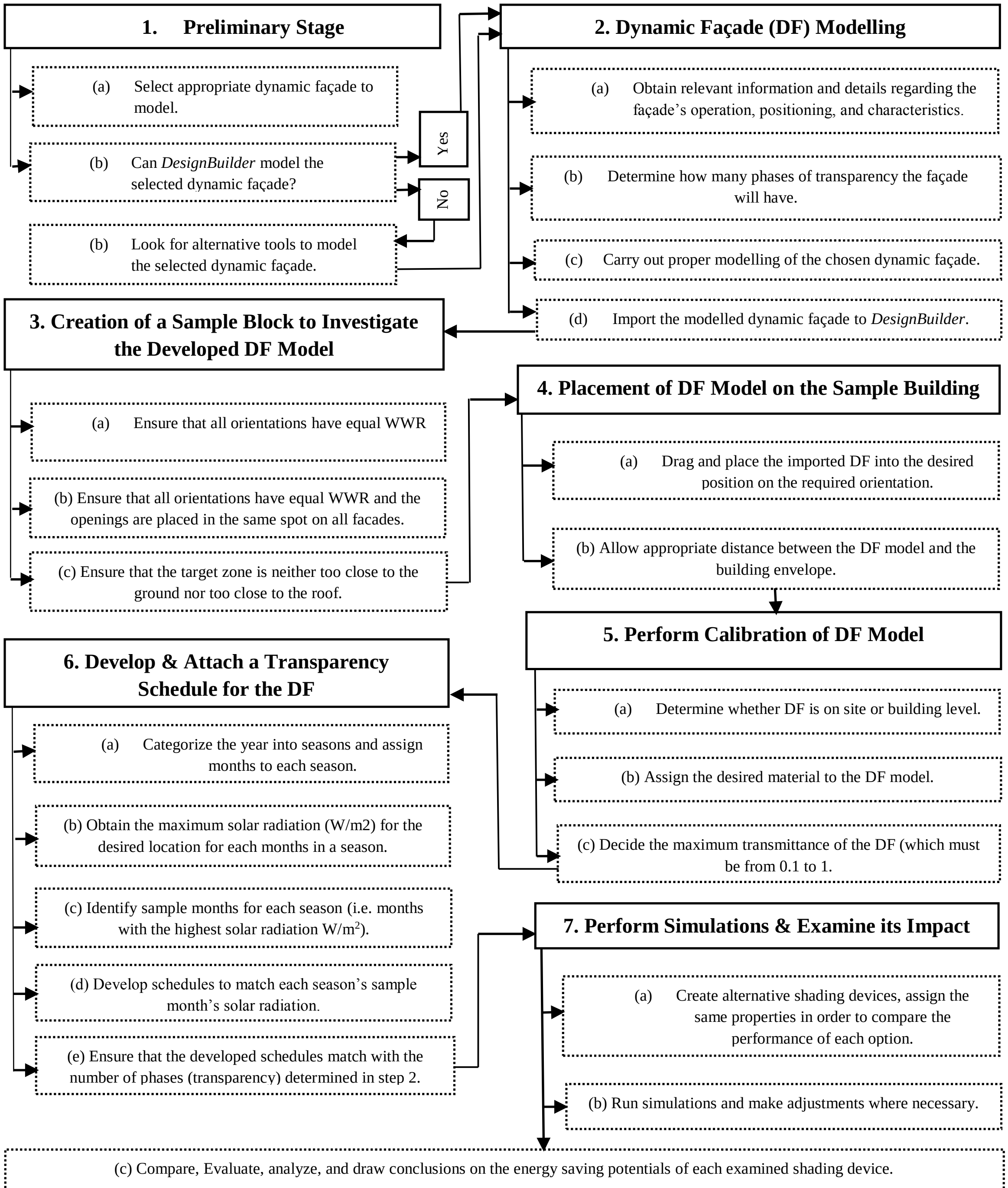


Figure 3.14 Flow Chart Showing how to Model DF & Examine its Impact

3.2 Adoption of Selected and Audited Office Building

Previous studies by Najid optimized the Heating, Ventilation and Air Conditioning (HVAC) system operation of an office building [11]. The building has been selected as a case study and is situated in the eastern province of KSA (Al-Khobar, Dhahran to be specific) [11]. The building is a representative of office buildings within this climate, it is practical and provides the required information to be used as inputs in modelling and simulation part of the research. The findings and recommendations of the thesis regarding the best practice among the HVAC system operation will be utilized while modelling the case study building.

3.2.1 Building Description

The chosen office building is squarely shaped and has its entrance placed along the eastern façade of the building. Figure 3.15 shows the site layout of the office building [11]. The nine floor office building is 30 m both in length and width and is 41 m high. The building has identical plans from first floor through third floor as well as from fourth floor through its seventh floors. The building's ground floor, the mezzanine floor as well as the eighth floor all have different plans. The mezzanine floor has a total floor space of 642 m^2 while all other floors occupy an area of 862 m^2 leading to 8400 m^2 as the total floor space of the building. Figure 3.16 shows images of the building in question [11].

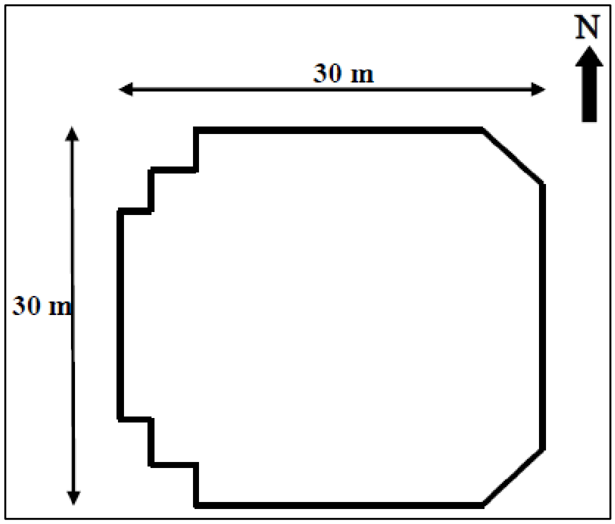
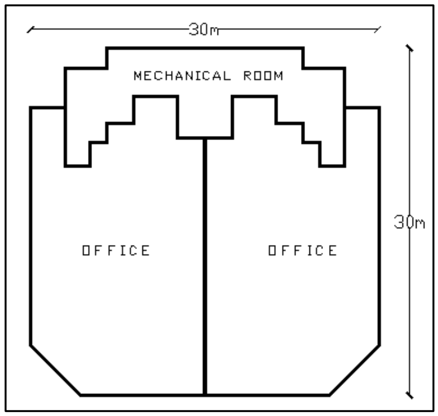


Figure 3.15 Layout of the office building [11].

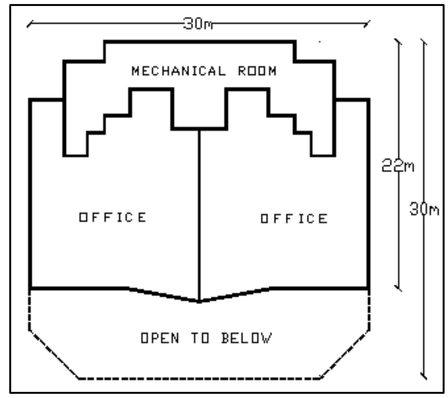
(a) Eastern façade (b) North-western facades (c) North-eastern facades

Figure 3.16 Views of the building [11].

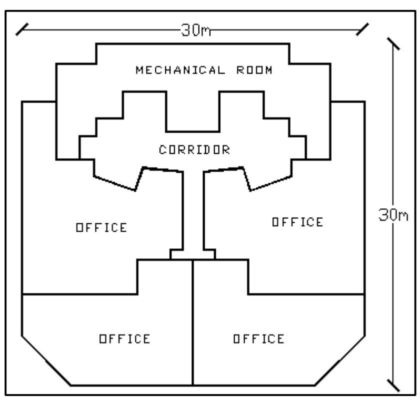
The building is equipped with *packaged single zone* (PSZ) HVAC systems and double-glazed (clear and tinted) glazing system. Interior work spaces constitute an open plan office arrangements [11]. The characteristics of this office building represent typical features of common office building found in Al-Khobar. Additionally, adequacy of data and location prompted the selection of the building as a case study [11]. Figure 3.17 shows floor plans of the selected building [11].



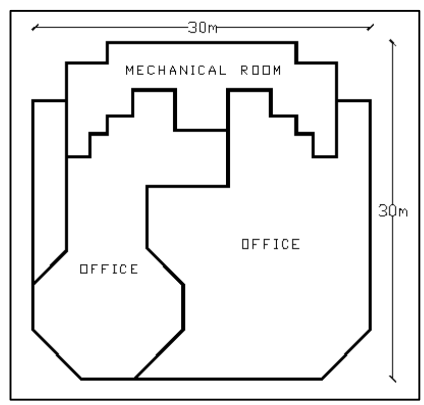
(a) Ground floor



(b) Mezzanine floor



(c) Typical first through seventh floor



(d) Eight floor plan

Figure 3.17 Building floor plans [11].

3.2.2 Building Envelope Details

The major parts of the building envelope composed of walls, external doors, slab-on-grade floor, window systems, and roof system. The architectural drawings provide the required details of the building's envelope system [11]. The components of the walls from the outside to the inside are granite cladding, concrete hollow block, and gypsum board and lastly paint on the inside [11]. 2.68 W/m^{2}°C was found to be the total U-value of the wall [11].

The roof system of the building from the topmost outside layer to the inside comprises an asphalt layer, 200 mm thick reinforced concrete slab and 15 mm cement plaster on the inside. Using Visual-DOE software, 4.01 W/m^{2}°C was calculated as the roof system's overall U-value [11]. 25 mm terrazzo forms the topmost floor layer of the building's slab-on-grade floor. This is placed on 25 mm sand-cement mortar. A 100 mm thick heavyweight mortar forms the base of the slab-on-grade floor. Figure 3.18 (a), (b), and (c) show wall, roof and floor cross-sections respectively [11].

The building exterior doors are made up of double clear glass doors [11]. Throughout the building, the window system comprises two (2) different forms of glazing systems [11]. Double clear glass was utilized in both the ground and the mezzanine floors [11]. Reflective-tinted double glazing windows were used for all typical 8 floors from first through eighth floors [11]. The WWR on the western and eastern facades (WWR) are 4% and 51% respectively [11]. The window-to-wall ratios for both the northern and southern facades were found to be 41% each [11]. Table 3.1 summarises other details of the building envelope [11].

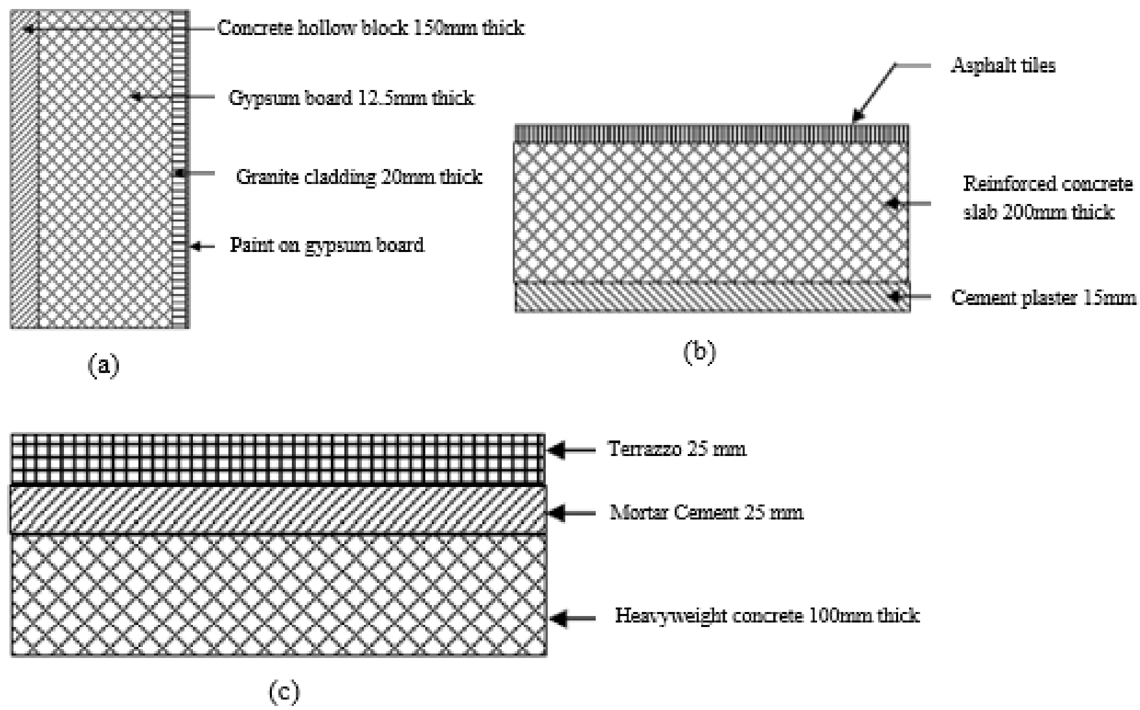


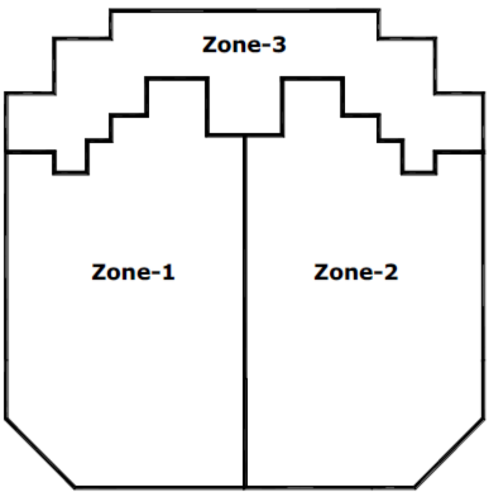
Figure 3.18 Building envelope details (a) Wall cross-section, (b) Roof cross-section and (c) Floor cross-section [11].

Table 3.1 Building envelope details [11].

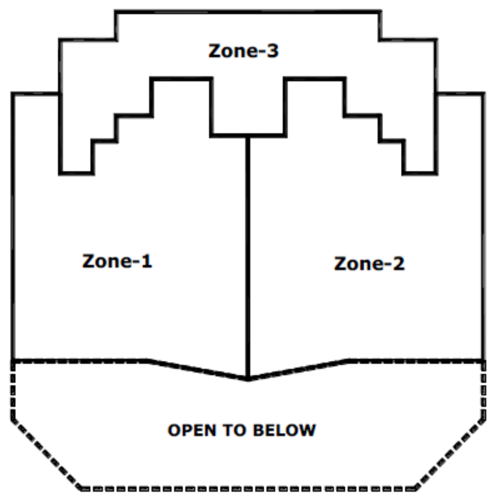
Characteristics	**Description**
Plan	Square
Total height of the building	41 m
Gross floor area	8400 m^2
Gross wall area	4690 m^2
Glazing area	2040 m^2
Overall WWR	43.5 %
Type of glazing	Double Glazed-Clear 6/6/6 mm, Reflective Double Glazed-Tinted 6/6/6 mm
External walls	Granite cladding 20 mm thick, Concrete hollow block 150mm thick, 12.5 mm thick Gypsum Board, , Paint on gypsum board
Roof	15mm Cement Plaster, 200 mm Thick Reinforced Concrete Slab, Asphalt Tiles
Floor	100 mm Heavyweight Concrete, 25 mm Mortar Cement, 25 mm Terrazzo

3.2.3 HVAC System Details

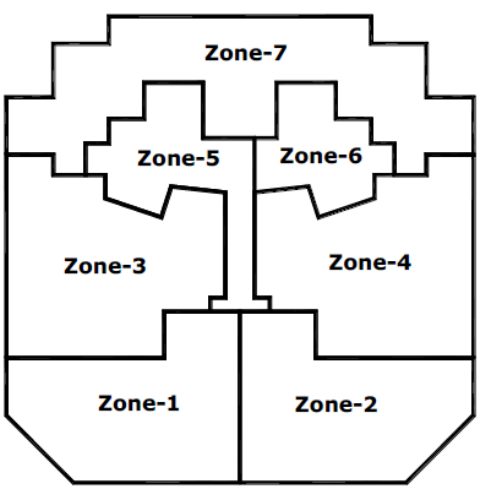
In order to determine the details of any f HVAC system, it is paramount to define the thermal zoning of the building [11]. Thermal zoning is simply defined as the subdivision and categorisation of spaces with varying thermal conditions in a building. That is, all spaces with similar thermal loads are categorised as one zone. Figure 3.19 illustrates graphically, the four (4) thermal zones within the building [11].



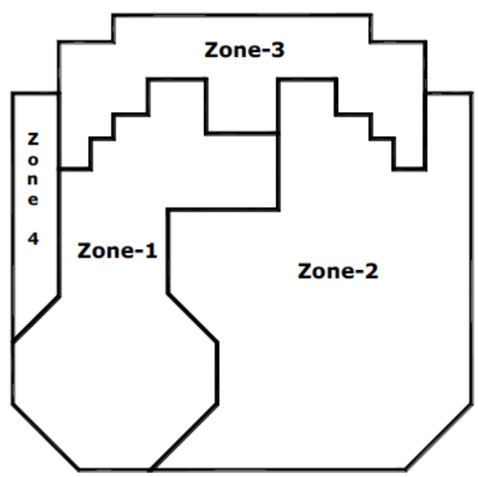
(a) Ground floor



(b) Mezzanine floor



(c) Typical first to seventh floors



(d) Eighth floor

Figure 3.19 Thermal zoning of the building [11].

Information obtained from the mechanical drawings of the building indicated that comfort is achieved by utilizing two (2) types of HVAC systems within the building. These are packaged single zone (PSZ) units and fan coil units (FCUs) [11]. PSZ units serve all the office zones while FCUs serve the corridors [11]. Table 3.2 provides basic information regarding the capacities, supply air flow rates and ventilation of the existing HVAC systems of the building. According to ASHRAE Handbook of Fundamentals [117], all air-tight buildings such as the one in question are assumed to have the following characteristics. An infiltration rate of 0.38 ACH, outdoor design conditions of 43°C, 7.5 mph and 24°C wind speed and indoor temperature respectively [121].

Table 3.2 Summary of HVAC system details [11].

Floor	Zone	Type of system	Capacities		Supply air flow		Ventilation	
			Tons	KW	cfm	l/s	cfm	l/s
Ground floor	Zone-1	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-2	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-3	Unconditioned zone						
Mezzanine floor	Zone-1	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-2	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-3	Unconditioned zone						
Typical first to seventh floor	Zone-1	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-2	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-3	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-4	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-5	FCU	3.5	12.33	1,400	660.69	0	0
	Zone-6	FCU	3.5	12.33	1,400	660.69	0	0
	Zone-7	Unconditioned zone						
Eighth floor	Zone-1	PSZ	30	105.50	10,500	4955.17	530	250
	Zone-2	PSZ	30	105.50	10,500	4955.17	178	84
	Zone-3	Unconditioned zone						
	Zone-4	Unconditioned zone						

3.2.4 Lighting Details

The electrical drawings provide information regarding light fixtures utilised in the building. Throughout the building, fluorescent lighting fixtures were utilised. Table 3.3 shows a detailed summary of the various kinds of fluorescent lighting fixtures used in the building. In order to obtain the lighting power density (LPD), the number of fixtures are multiplied by power of lamps for each fixture type. The LPD is calculated based on zones of the building. Table 3.4 illustrates the summary of calculated LPD for various zones of the building [11].

Table 3.3 Types of lighting fixtures [11].

Description	Wattage	Voltage
Fluorescent light with above mirror, rapid start	20	127
Wraparound fluorescent fixture with prismatic diffuser, rapid start	40	127
Wraparound fluorescent fixture with prismatic diffuser, rapid start	2x40	127
Industrial Type wraparound fluorescent fixture with prismatic diffuser	2x40	127
Fluorescent fixture with fully anodized louver	4x18	127
Spot light with ring	50	127

Other relevant information regarding the building are documented and summarized in Table 3.5 [11]. The table presents information on physical and operational features of the building as well as information covering the HVAC system, lighting and equipment obtained during the audit process [11].

Table 3.4 Building LPD of each zone [11].

Floor	Zone	LPD(W/m^2)
Ground Floor	Zone-1	11.2
	Zone-2	10.9
	Zone-3	21.5
Mezzanine floor	Zone-1	14.6
	Zone-2	14.6
	Zone-3	21.5
Typical first to seventh floor	Zone-1	13.6
	Zone-2	13.6
	Zone-3	15.3
	Zone-4	15.3
	Zone-5	20.2
	Zone-6	24.6
	Zone-7	21.5
Eighth floor	Zone-1	18.8
	Zone-2	12.1
	Zone-3	21.5
	Zone-4	0.0

Table 3.5 Summary of building physical and operational characteristics [11].

Characteristics	Description
Location	Al-Khobar, Saudi Arabia
Type of building	Office
Plan shape	Square
Total height	40.730 m
Gross floor area	8400 m^2
Gross wall area	4690 m^2
Window area	2040 m^2
Overall WWR	43.5 %
Type of glazing	Double Glazed-Clear 6/6/6 mm, Reflective Double Glazed-Tinted 6/6/6 mm
Total no. of people	400
Operating hours	Ramadan: 7:00am to 3.30pm on all working days for 65% of occupants, Remaining 35% of occupants- Sat. to Tue.-7:00am to 5.30pm, Wed.-7:00am to 3:30pm. Normal Days: Sat. to Tue.-7:00am to 5.30pm, Wed.-7:00am to 3:30pm
External walls	Granite cladding cut to size 20mm thick, Concrete hollow block 150mm thick, 12.5mm thick Gypsum Board, , Paint on gypsum board
Roof	15mm Cement Plaster, 200mm Thick Reinforced Concrete Slab, Asphalt Tiles
Floor	100 mm Heavyweight Concrete, 25 mm Mortar Cement, 25 mm Terrazzo.

		Ground Floor			Mezzanine Floor			Typical First to Seventh Floor							Eighth Floor			
		Zone1	Zone2	Zone3	Zone1	Zone2	Zone3	Zone1	Zone2	Zone3	Zone4	Zone5	Zone6	Zone7	Zone1	Zone2	Zone3	Zone4
Occupant density (m^2/person)		23.5	23.5	-	35.3	35.3	-	24.5	24.5	20	20	-	-	-	51	80	-	-
Lighting Power Density (LPD) (W/m^2)		11.2	10.9	21.5	14.6	14.6	21.5	13.6	13.6	15.3	15.3	20.2	24.6	21.5	18.8	12.1	21.5	0
Equipment Power Density (EPD) (W/m^2)		15.7	14.9	0	10.9	10.1	0	24.6	24.6	19.8	19.8	0	0	0	9.7	5.4	0	0
HVAC system type		PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	FCU	FCU	PSZ	PSZ	PSZ	PSZ	PSZ
Supply Temperature (°C)		13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
Thermostat Setpoint temperature (°C)	Summer	21	21	-	21	21	-	21	21	21	21	21	21	-	21	21	-	-
	Winter	24	24	-	24	24	-	24	24	24	24	24	24	-	24	24	-	-
Total ventilation air flow rate for each zone (l/s)		375	375	0	375	375	0	180	180	180	180	0	0	0	250	84	0	0

Legend: WWR=Window to Wall Ratio; PSZ = Packaged Single Zone; FCU = Fan Coil Unit

3.3 Development of Base Case Model (Static)

Findings and recommendations from previous research helped in developing the building model. However, limited information was available. The developed model in the previous research was not within reach. As such, a replica of the original model was developed using one of the state-of-the-art Energy Analysis Tools (EAT).

Visual-DOE software was used to develop the building model in the previous research. *Visual-DOE* tool is considered less sophisticated and obsolete (compared to other state-of-the-art EAT. Therefore, Findings and recommendations from the previous research were utilized in *DesignBuilder* to model the building. Little or no information was provided on how the previous model was developed in *Visual-DOE*. As such, various steps were undertaken in order to accurately and effectively model the building. Thus, the steps undertaken are described below:

3.3.1 Phase I: Site Inventory

This was conducted in order to observe, compare, and confirm documented building characteristics from the previous research and what is actually in place. The building is one of Al-Karawan’s twin towers. Permission was first secured from the building management authority to carry out the exercise. A walkthrough at the ground floor confirmed the building plan. The building envelop was then thoroughly examined. Emphasis was placed on WWR and the finishing materials of the envelope. Respective orientations of the building were examined. Figure 3.20 (a-c) presents the views of the building.

(a) North-East facing facades

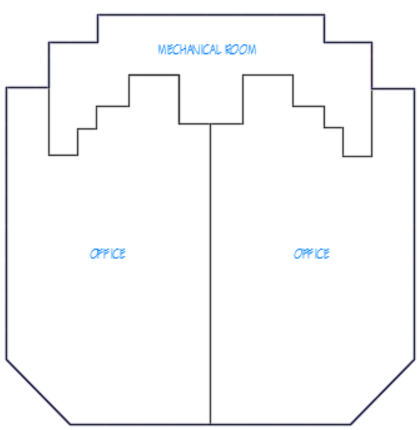
(b) South-East facing facades

(c) West facing facade

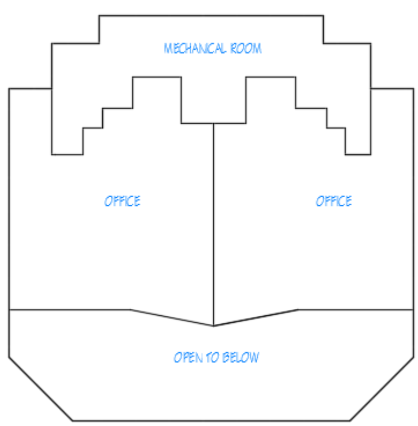
Figure 3.20 Views of the Building

3.3.2 Phase II: AutoCAD Utilization

Sketches from previous work on the building only provided the overall layout dimensions. That is, only overall external dimensions (out-to-out) were provided. Obtained images were scaled and all floor plans were generated therefrom. These were Ground, mezzanine, identical first to seventh floor plans and eight floor plans. Figure 3.21 (a-d) illustrates the generated floor plans.



(a)



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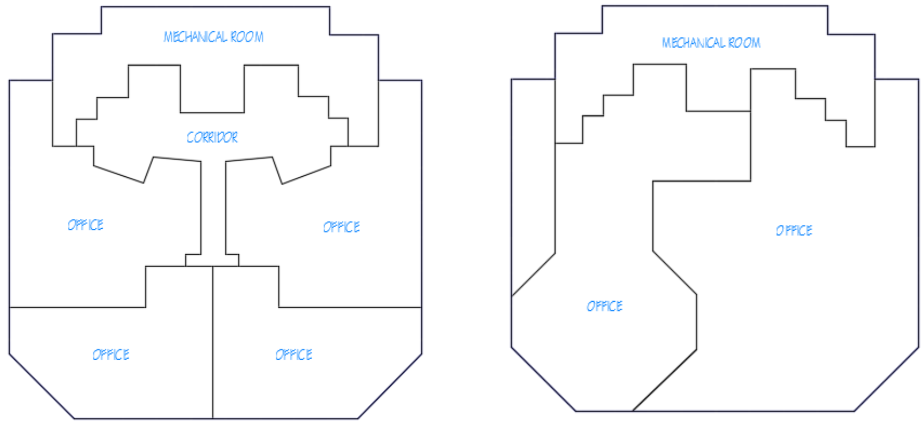


(c) (d)

Figure 3.21 Generated Floor Plans: (a) Ground floor, (b) Mezzanine floor, (c) Typical first-seventh floors, and (d) Eighth floor.

3.3.3 Phase III: *DesignBuilder* Involvement

DesignBuilder involvement began with the importation of developed floor plans from AutoCAD. Individual floors were created in *DesignBuilder* using the *AddBlock* command. Respective HVAC zones were then created with the information obtained from previous research. First floor plan was *cloned* to generate identical floor plans (1^{st}-7^{th} floors). Upon completing the block model, obtained information was then used for the calibration exercise.

The building was calibrated on both *site* and *building* levels. At *site level*, *location* and *region* properties were specified. These properties were *location template*, *simulation weather data* and the country where the building *region* (Saudi Arabia) is situated. At the building level, *model options data* were first specified. The *model options data* determine the nature of building activities and its operative principles. Thereafter, data were specified under *activities, construction, openings, lighting and HVAC sub headings.*

Importantly, all specified data were strictly based on obtained building information. Reported *WWR* of 43.5% was achieved by manually drawing all openings. Similarly, all specifications and other recommendations regarding energy savings from previous research were implemented in the course of modelling. Thus, the implemented recommendations were combinations of all potential *ECMs*. These potential *ECMs* were:

- Set-point temperature of 24^0C during occupied hours.
- Implementation of night-time setback in set-point temperature.
- Average ventilation airflow rate of 5 L/s-person.
- Provision of ventilation only during occupied hours.
- Evaluation of all all-air Variable Air Volume (VAV) HVAC system types.

Figure 3.22 (a-c) shows cross sections of *external walls*, *floor,* and *roof* as created in *DesignBuilder.* Various schedules assigned during the course of modelling the building are illustrated in Figure 3.23 (a-j).

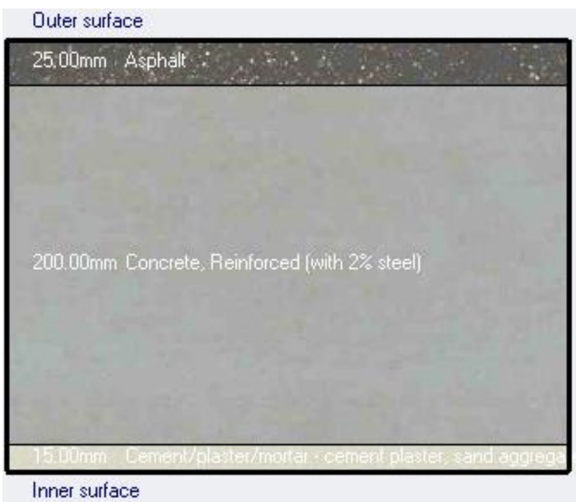
Simulations were conducted in order to select the best energy efficient HVAC system. Packaged HVAC system was equally evaluated alongside the VAV systems. In the previous research VAV HVAC system (Cooling capacities and airflow auto sized) with variable speed drive as airflow control option proved to be the best energy efficient HVAC system. However, VAV, Air-cooled Chiller, HR, Outdoor air reset + mixed mode HVAC system was the best energy efficient HVAC system in this context. Therefore, VAV, Air-cooled Chiller, HR, Outdoor air reset + mixed mode HVAC system is regarded as the best practice. Finally, obtained results were examined, analyzed and discussed in Chapter 5.

The next big step involved the introduction of *Window shading system* to the best practice. This was carried out in order to investigate the impact of embedded shading alternatives in *DesignBuilder*. 4 types of window shading alternatives were positioned on the outside and controlled via a horizontal solar and an operation schedule. The 4 window shading types examined were: Drapes - open weave medium; Shade role - medium translucent; Venetian blinds - medium (modelled as diffusing); and Blind with medium reflectivity slats. The operation schedule used in controlling the examined window shading alternatives is shown in Figure 3.24. The performance of the investigated alternatives is presented in Chapter 4.

Furthermore, the introduced *Window shading system* to the best practice was replaced with a designed dynamic façade placed 0.8m away from the building envelope. The introduced dynamic façade mimics the mode of operation of *User-controlled Dynamic Façade* as utilized in Kiefer Technic Showroom. The performance of the dynamic façade was examined and comparisons drawn between the performance of dynamic façade and the embedded window shading alternative. Chapter 4 elaborates on this analysis.

(a)

(b)



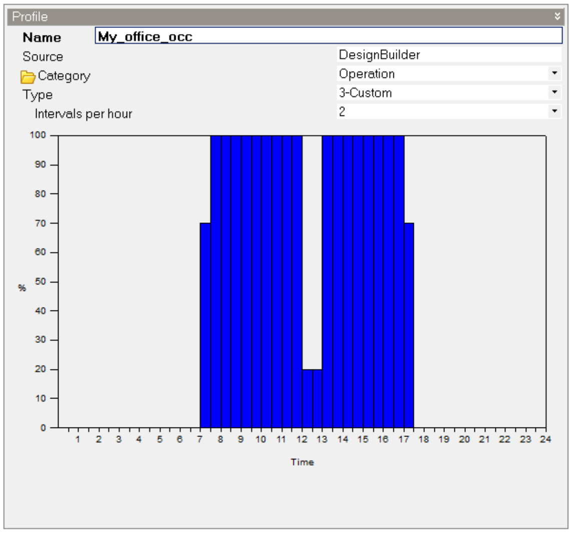
(c)

(a) Cross section of external walls.

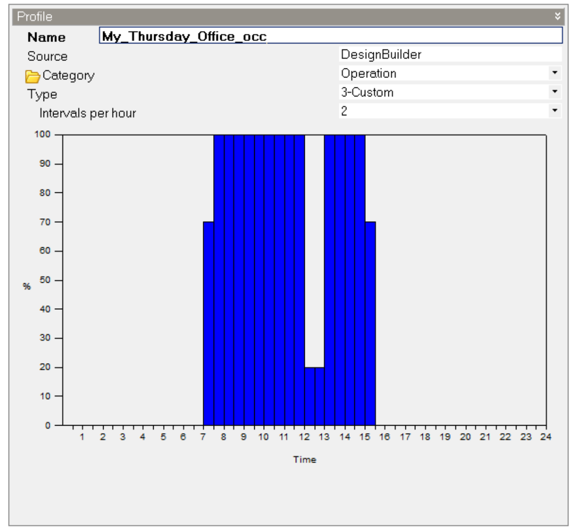
(b) Cross section of a ground floor.

(c) Roof cross section.

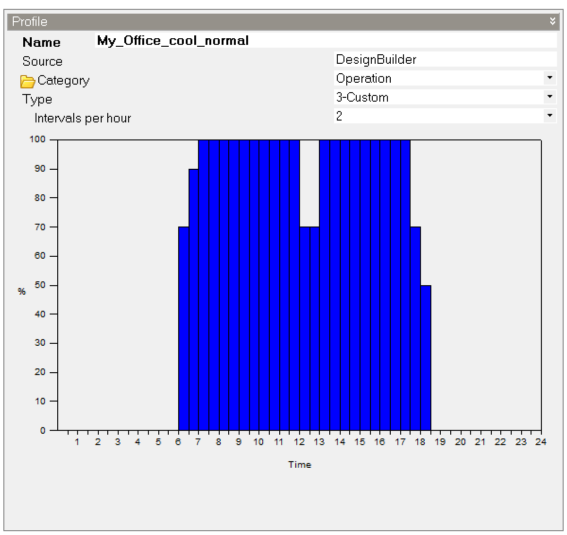
Figure 3.22 Cross sections of building components.



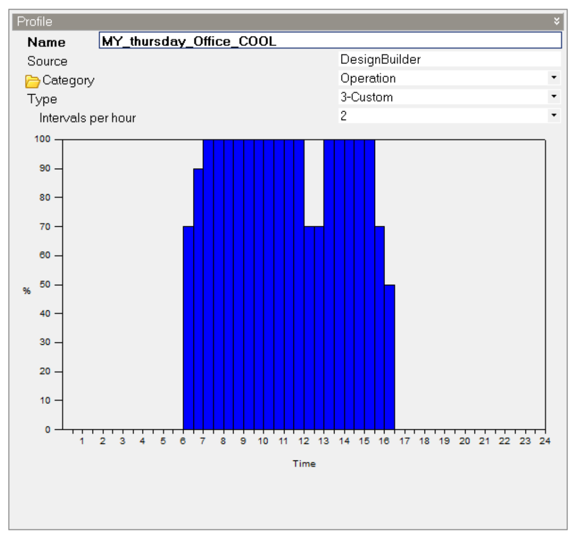
(a)



(b)



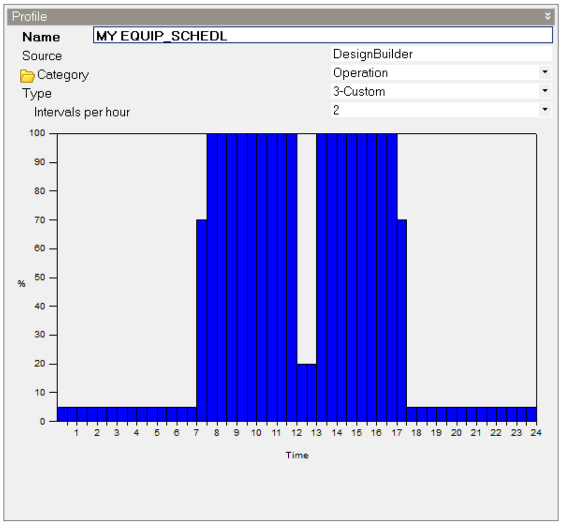
(c)



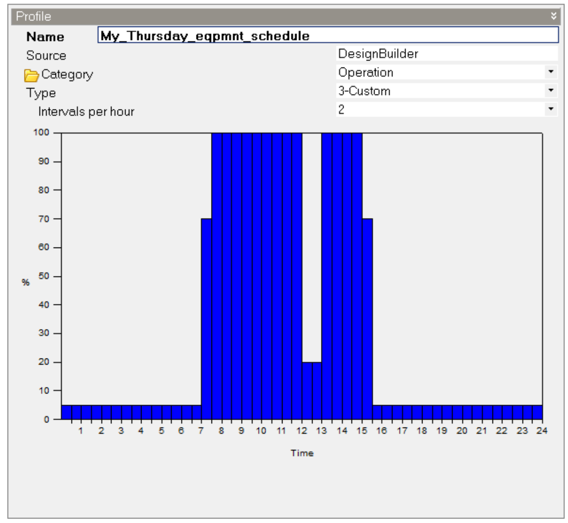
(d)

(a) Normal day occupancy schedule. (b) Thursday occupancy schedule.

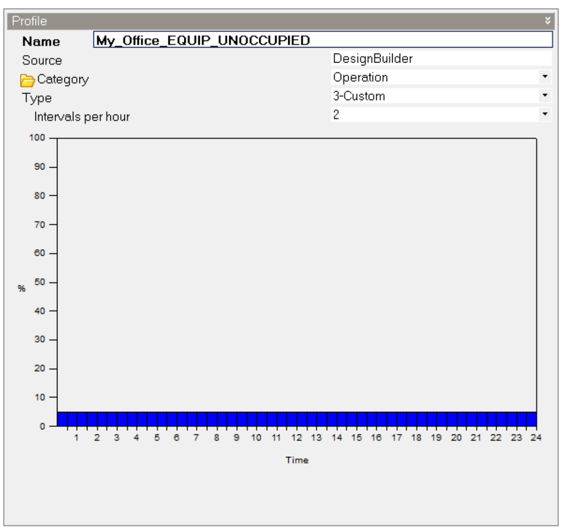
(c) Normal day cooling schedule. (d) Thursday cooling schedule.



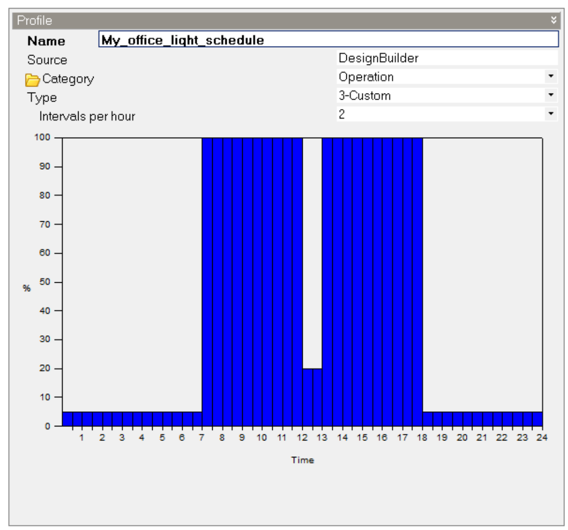
(e)



(f)



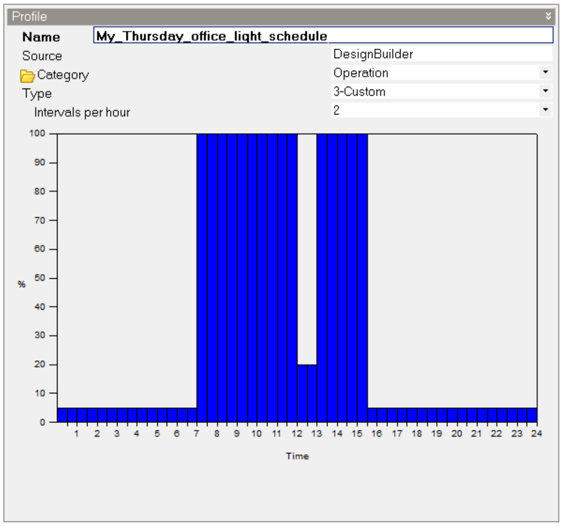
(g)



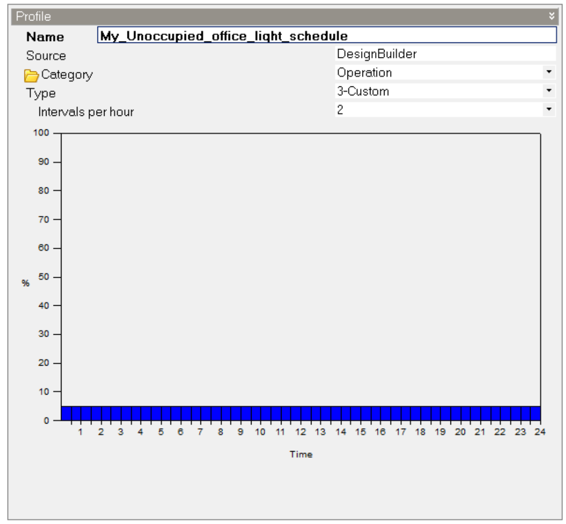
(h)

(e) Normal day equipment schedule. (f) Thursday equipment schedule.

(g) Weekend equipment schedule. (h) Normal day light schedule.



(i)



(j)

(i) Thursday light schedule. (j) Weekend light schedule.

Figure 3.23 Operation Schedules for Base Case Model (Static).

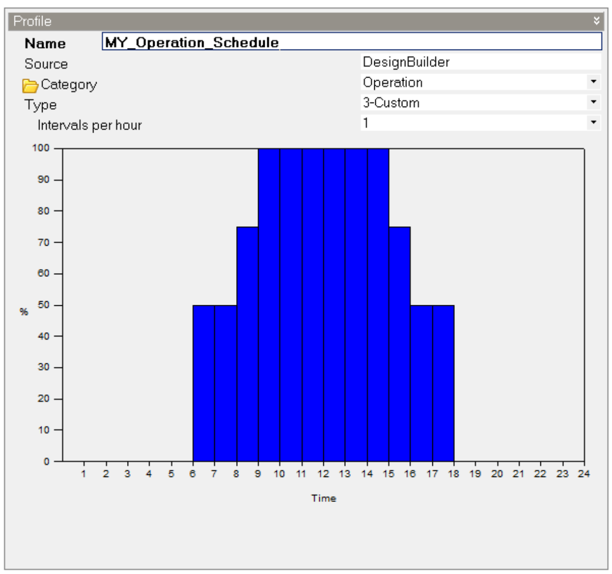


Figure 3.24 Operation Schedule of Window Shading Alternatives.

The developed dynamic shade operates in 10 different stages of transparencies. The transparencies are 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% placed from the ground floor to the 8th floor respectively across the building. Therefore when the façade is fully opened, a maximum transparency of 90% is achieved. The dynamic shades are controlled using a general operation schedule, an East-orientation sensitive schedule, and a South-orientation sensitive schedule as the case may be. Figure 3.25 illustrate the dynamic shades and the percentages of their transparencies on the office building floors.

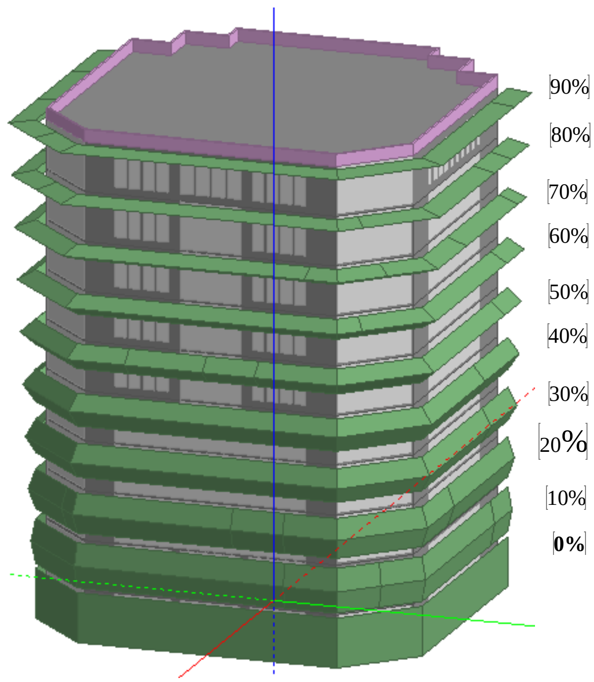
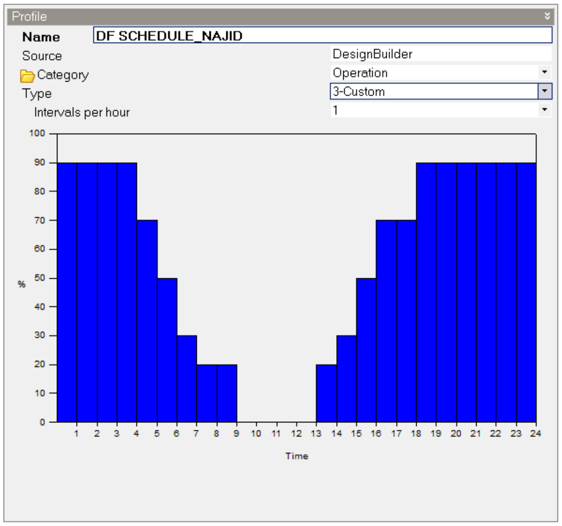
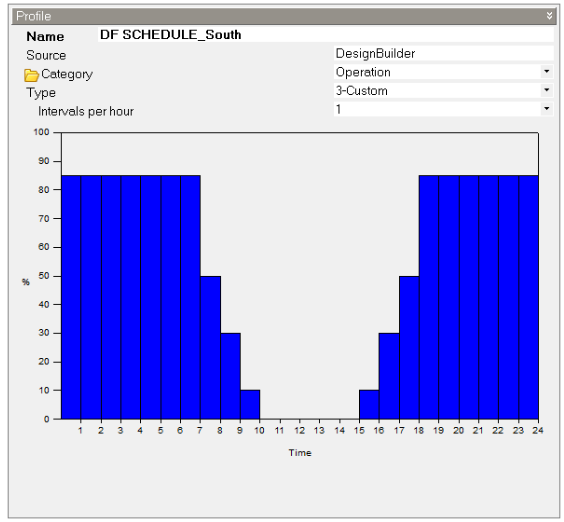


Figure 3.25 Mode of Operation of the Dynamic Shades.

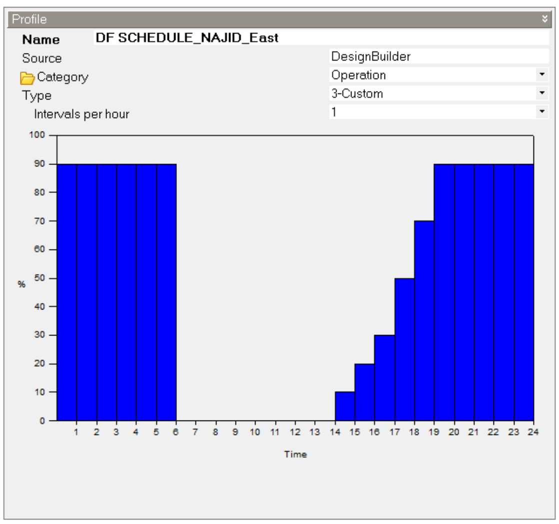
A general operation schedule was first applied to the dynamic shades. The schedule was then tailored to satisfy the solar radiation requirements of different orientations. The West orientation had small openings, so dynamic shade not applied on that orientation. The South and East orientations are more prone to high solar radiations than the North. Therefore, the general operation schedule was edited to suit the South and East orientations. Figure 3.26 (a-c) illustrate general, South, and East orientation schedules respectively.



(a)



(b)



(c)

(a) General operation schedule.
(b) South-orientation sensitive schedule.
(c) East-orientation sensitive schedule.

Figure 3.26 Operation Schedules of Dynamic Shades.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the evaluations of examined energy saving alternatives. Evaluations were carried out and important milestones were achieved. Outcomes are graphically presented in each case for clarity, easy understanding and comparison purposes. The results are categorized in to 3 major sections. Namely:

(i) Examining the energy performance of dynamic facades on a theoretical base case office building.

(ii) Investigations to determine the best HVAC system.

(iii) Investigating the energy performance of dynamic facades on a real base case office building.

4.2 Investigating the Energy Performance of Dynamic Facades

Various investigations were carried out for different reasons on the developed theoretical base case office building. The first investigation involved examining whether or not, *DesignBuilder* recognizes dynamic facades and take them into account while calculating energy consumption or related aspects. The impact of shading devices on individual parameters that add up to total cooling energy consumption was equally investigated among other various investigations conducted.

4.2.1 Dynamic Facades in *DesignBuilder*

The possibility of dynamic facades working in *DesignBuilder* environment was investigated. In this regard, energy consumption required in providing total cooling for a typical summer day has been investigated. The investigation was conducted on 2 alternatives with the same characteristics. The 2 alternatives were: (a) the building with dynamic façade attached; and (b) the building without any shading elements of any kind. The dynamic façade was positioned 1 m away from the building envelope on all the orientations of a typical floor of the building. Figure 4.1 and Figure 4.2 illustrate the energy consumption in providing total cooling for a typical summer day (July 21st) on east and west zones of the typical floor respectively. The alternative without any shading element is considered as the base case (theoretical). As such, the energy performance of dynamic façade was compared to the base case.

As observed, early morning sun in Figure 4.1 has resulted in significantly high consumption of energy in providing cooling on the East zone in the base case. However, dynamic facade showed reduced energy consumption on the same zone. Dynamic façade achieved reduction in 52.3% (-52.3%) energy savings on the east zone compared to the base case. Similarly, in Figure 4.2, dynamic facade was able to reduce the cooling load posed by late afternoon sun on the west zone. An energy saving of 47.7% (-47.7%) was recorded by dynamic façade on the west zone compared to the base case. Therefore, *DesignBuilder* does recognize dynamic facade and takes it into account in its calculations. The negative sign (-) indicates energy savings in all instances.

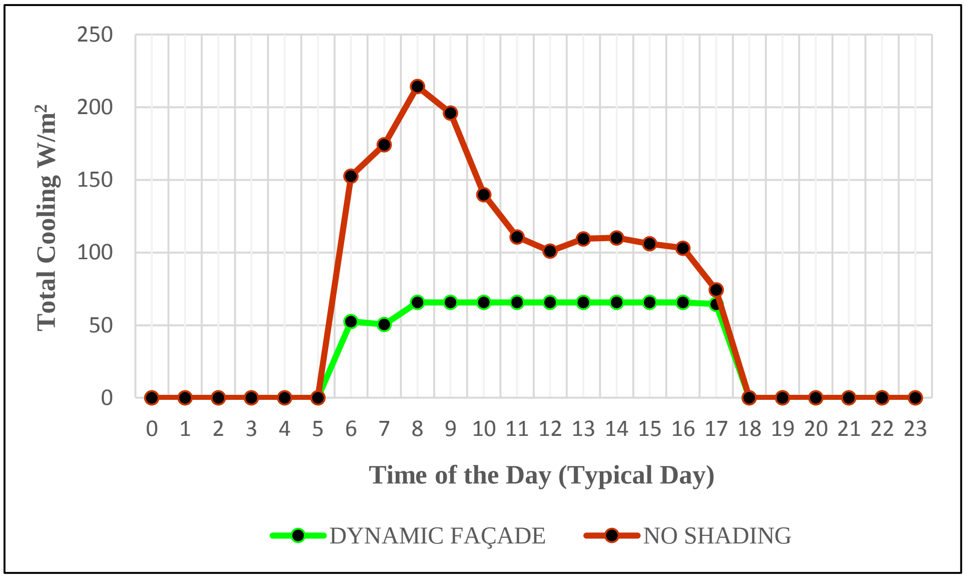


Figure 4.1 Daily Energy Consumption for East Zone (July 21st)

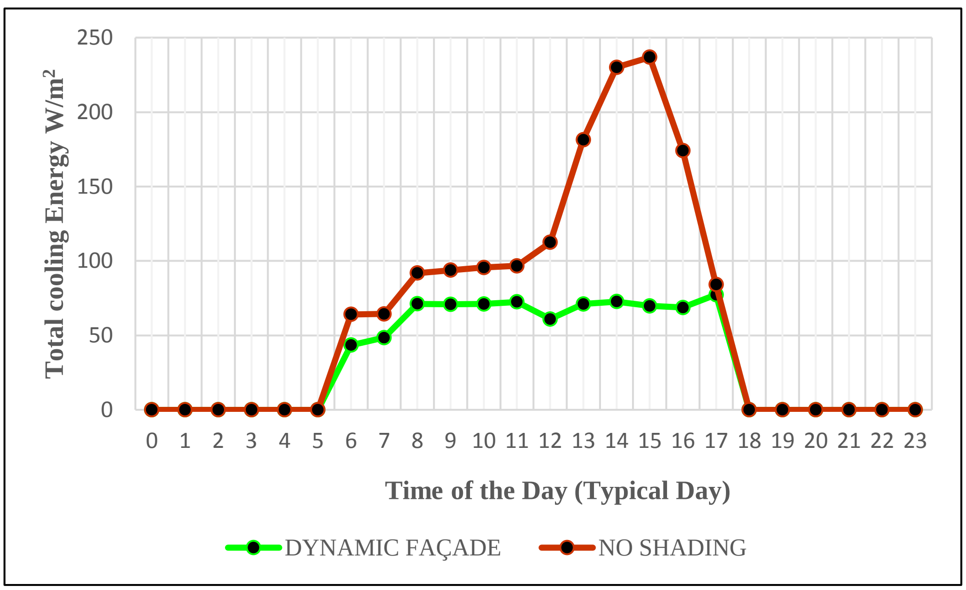


Figure 4.2 Daily Energy Consumption for West Zone (July 21st)

Further investigation in to the total cooling load on an annual basis for the whole floor equally demonstrated the impact of dynamic facade. *Dynamic facade* produced a cooling load saving of 34.9% (-34.9%) compared to the base case. The energy performance of dynamic façade on all the zones of a typical floor is illustrated in Figure 4.3. Therefore, the workability of dynamic facades in *DesignBuilder* has been confirmed.

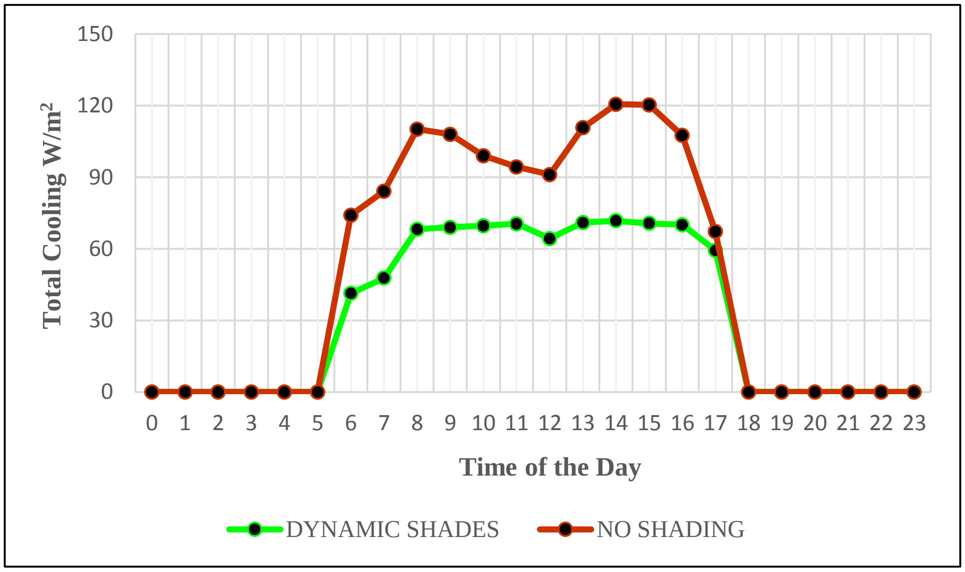


Figure 4.3 Daily Total Cooling Energy _Typical Floor (July 21st)

To satisfy the second objective, thermal comfort was maintained throughout the simulation exercise. Fanger Predicted Mean Vote (PMV) model ensured that thermal comfort was achieved with reduced total cooling loads. Fanger models graphically show how thermal comfort was maintained on the east and west zones of the typical floor. The models graphically indicate that even with the cooling load savings reported in Figure 4.4 and Figure 4.5 due to dynamic façade incorporation on the east and west zones of the typical floor. As observed throughout the day (typical summer day) the values fall within the acceptable range of +0.6 – (-0.6). It should be noted that only the occupied hours were considered in both Figure 4.4 and Figure 4.5. On the same note, no discomfort hour was recorded throughout the day on both east and west zones of the typical floor.

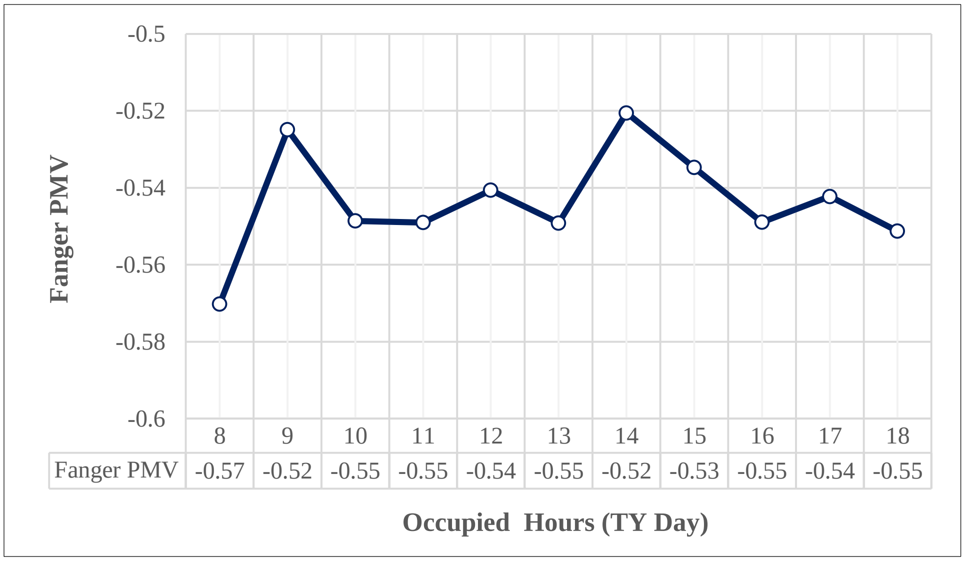


Figure 4.4 Daily Fanger PMV (East _ July 21st)

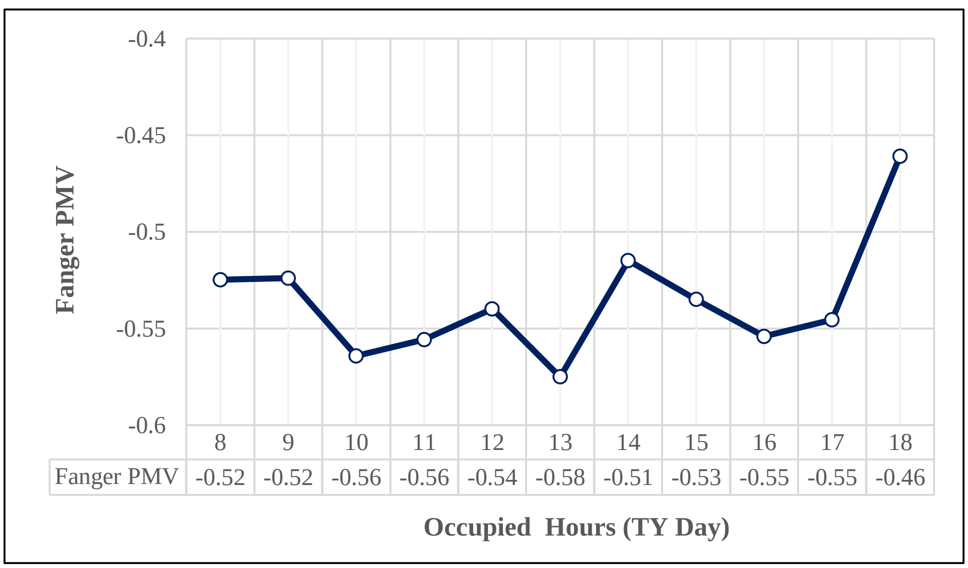
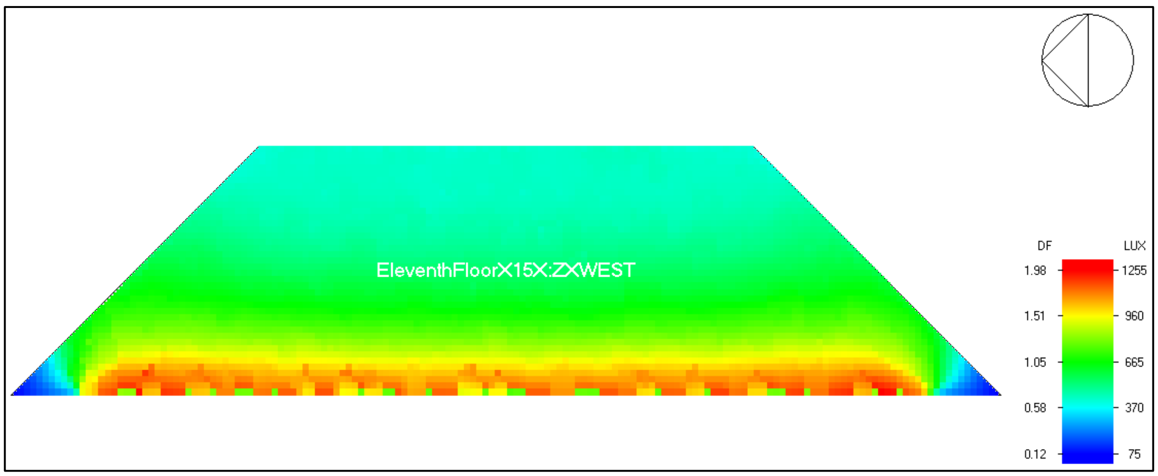
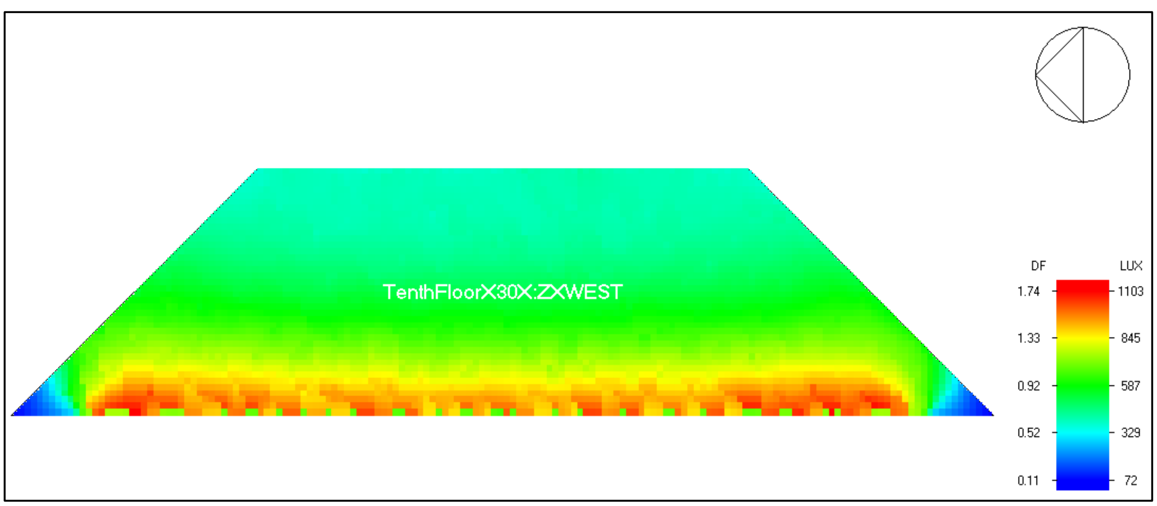


Figure 4.5 Daily Fanger PMV (West _ July 21st)

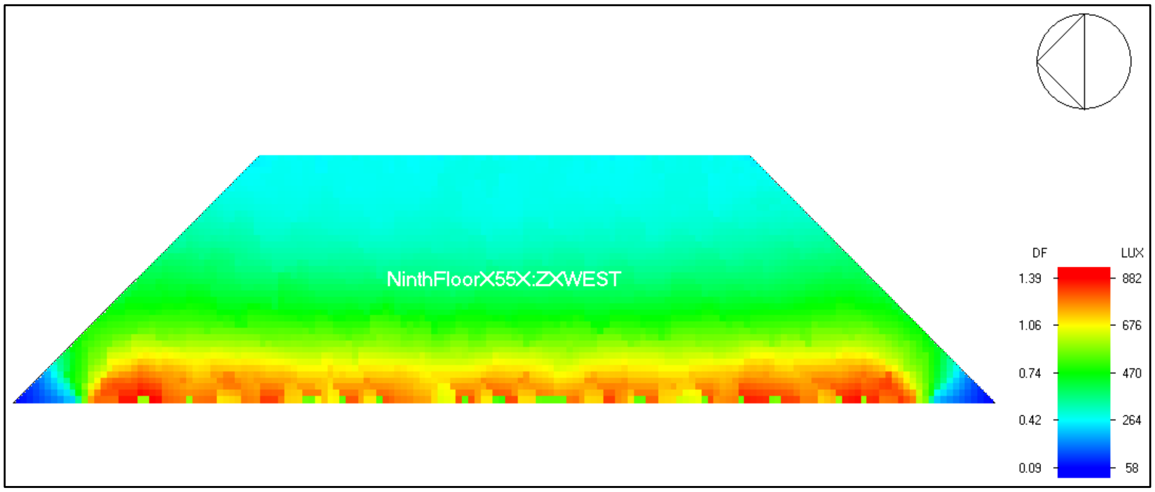
Daylight analysis was also conducted on the west zone to prove that visual comfort was not compromised in an attempt to reduce energy consumption. It was observed that the intended light of 500 lux was achieved in most part of the zone. The daylight analysis on the west zones of different floors to depict the lighting behavior under different transparencies of the dynamic façade for July 21 as indicated in Figure 4.6 (a-d). Lighting control was enable and 2 sensors were placed for the daylight analysis. Sensor 1 covered 30% while sensor 2 covered 70% of the floor's lighting area. Sensor 2 covered the larger floor area close to the opening while sensor 1 covered 30% of the floor area deep inside the floor area. Figure 4.6 (a-d) show daylight analysis where 85%, 70%, 45%, and 20% transparencies are utilized throughout the day respectively.



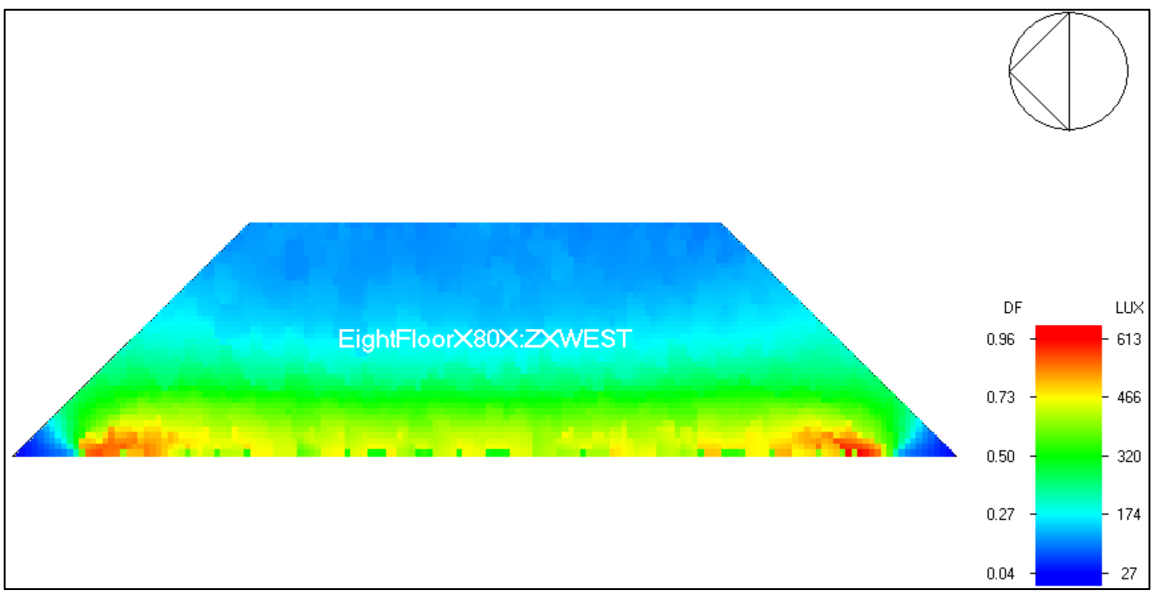
(a) Daylight Analysis with 85% DF transparency throughout the day (West_July 21)



(b) Daylight Analysis with 70% DF transparency throughout the day (West_July 21)



(c) Daylight Analysis with 45% DF transparency throughout the day (West_July 21)



(d) Daylight Analysis with 20% DF transparency throughout the day (West_July 21)

Figure 4.6 Daylight Analysis of Different DF Transparencies (West_July 21st)

The impact of dynamic façade was further examined on the East and West zones of the same model but this time without enabling lighting control. This is to provide alternative to anyone who intends to use dynamic façade without lighting control. Here, dynamic façade saved 42.1% kWh/m^2 and 39.1% kWh/m^2 total cooling load on the East and West zones of a typical floor respectively compared to the base case.

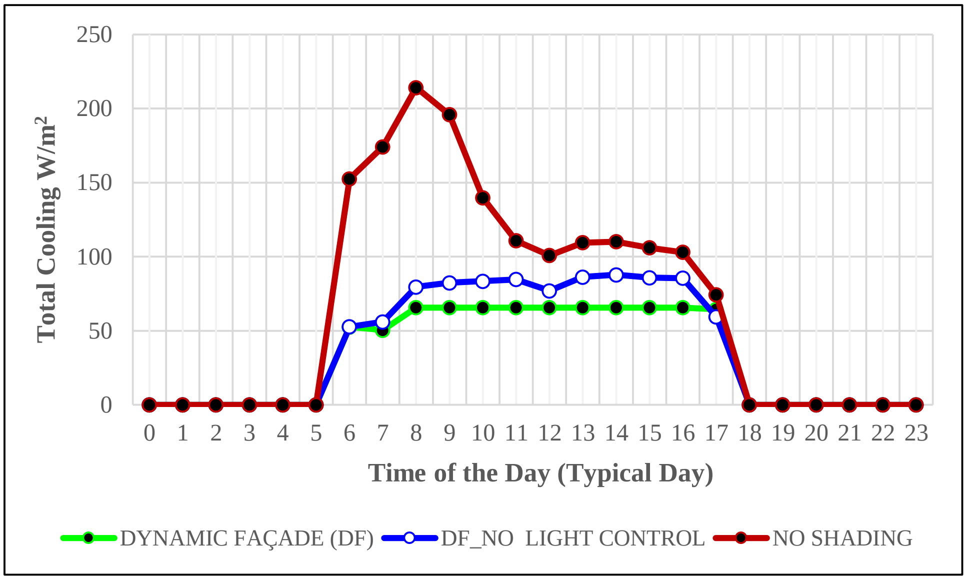


Figure 4.7 Energy Performance of DF East Zone (July 21st)

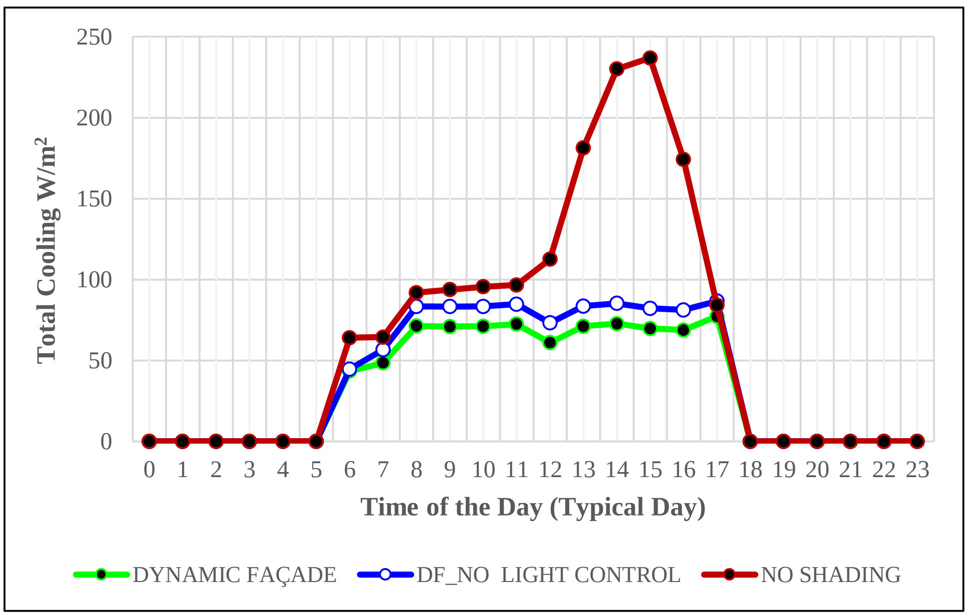


Figure 4.8 Energy Performance of DF West Zone (July 21st)

In comparison with the model in which lighting control was integrated, dynamic façade saved 10.2% more energy (i.e. 52.3%) on the East zone and 8.6% more total cooling load (i.e. 47.7%) on the West zone respectively. Figure 4.7 and Figure 4.8 illustrate the energy performance of dynamic façade without lighting control on the east and west zones respectively. The energy performance of the dynamic façade is compared with the base case without shading.

4.2.2 Impact of Shading Devices on Load Parameters

It is important to investigate the impact of shading devices on the different parameters that lead to the total cooling energy (TCE) consumed in a building. As such, the impact of dynamic facade was investigated on the West zone of a typical floor for a typical summer day (July 21). The essential parameters responsible for TCE in a building are solar gains exterior windows, zone sensible cooling, and lighting energy consumption.

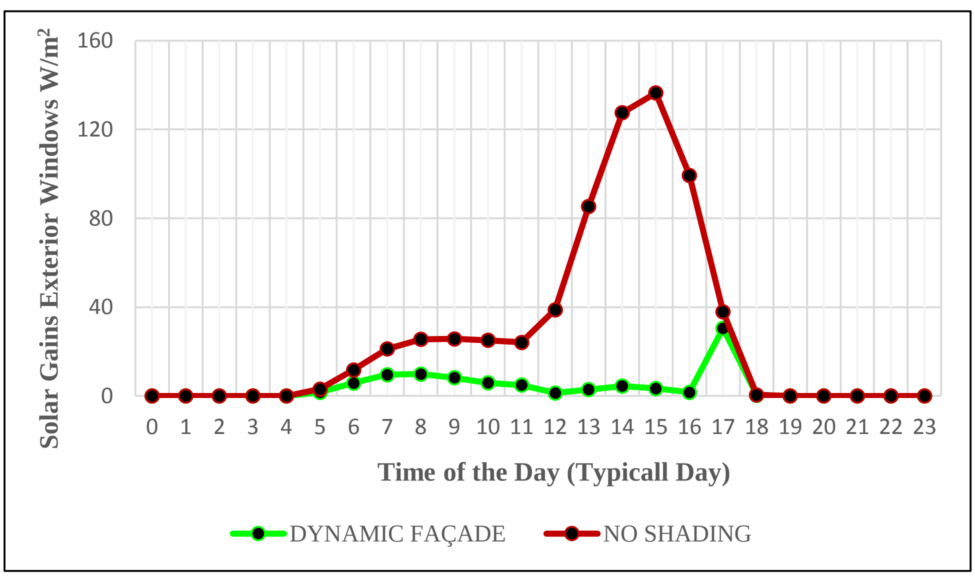


Figure 4.9 Solar Gains Exterior Windows (West) W/m^2

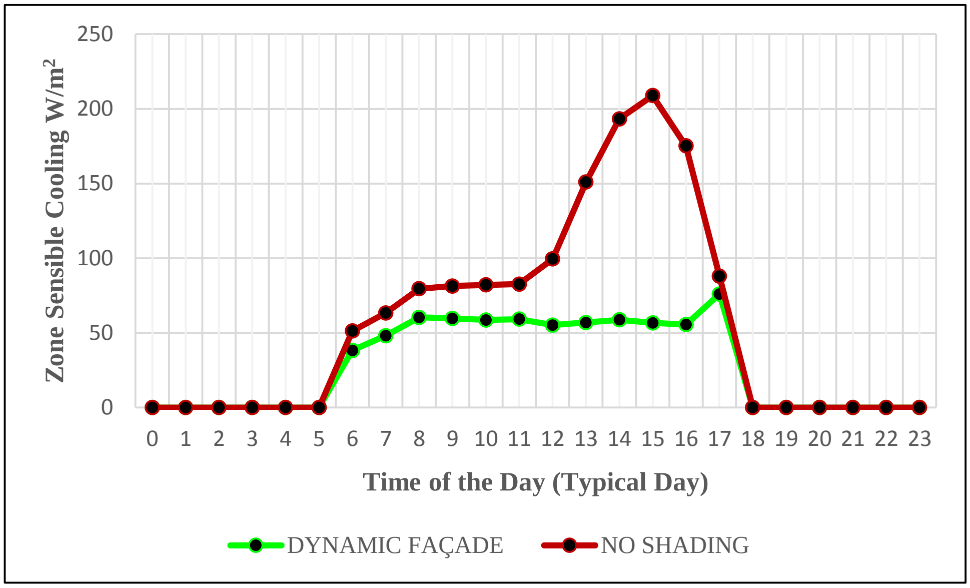


Figure 4.10 Zone Sensible Cooling (West) W/m²

The performance of dynamic shades in relation to the base case was examined on the 3 key parameters. Figure 4.9 presents the performance of the dynamic facade on solar gains exterior windows. Here, *dynamic facade* saved 86.3% (-86.3%) compared to the base case. That is, dynamic façade reduced solar gains exterior windows by 86.3% from getting into the west zone of the building. Obtained results from zone sensible cooling is illustrated in Figure 4.10. *Dynamic facade* achieved a saving of 49.6% (-49.6%) while compared to the base case.

However, in lighting energy consumption, dynamic facade consumed 3 times more energy than the base case. This is because dynamic facade blocks daylight while blocking solar radiation. Figure 4.11 presents the outcome of lighting energy consumption graphically. Therefore, the performance of dynamic facade with regards to the respective parameters discussed above lead us to the TCE as presented in Figure 4.2.

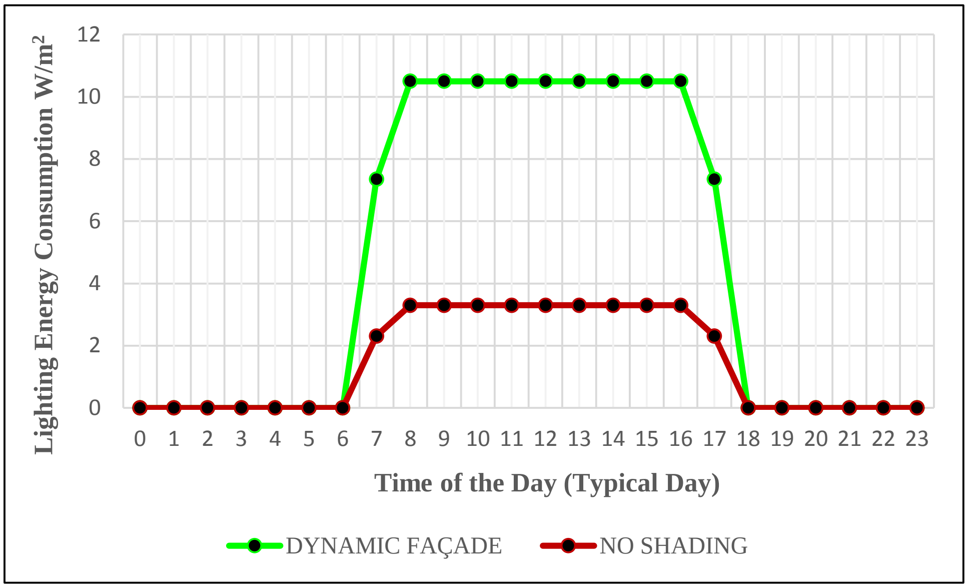


Figure 4.11 Lighting Energy Consumption (West) W/m²

4.2.3 Methods of Achieving Dynamic Facade in *DesignBuilder*

Dynamic façade can be achieved in *DesignBuilder* using a number of techniques. 2 techniques of achieving dynamic façade in *DesignBuilder* have been examined on the theoretical base case office building. Again, a typical summer day was selected for this exercise. In the first technique, the 7th floor was selected in which a fully closed *dynamic facade* (0% transparent) was positioned. The transparency of the *dynamic facade* was then controlled using an operation schedule. In the second technique, all the floors in the target zones were examined. The transparency of the *dynamic facade* is hereby controlled by the geometry of the *dynamic facade*. As such, an operation schedule was not required to control the operation or transparency of the *dynamic facade* in any of the target floors. Instead, the operation schedule only provided guidance in knowing the exact floor(s) to read values as the day progresses. In both techniques, total cooling load (TCL), solar gains exterior windows (SGEW), and lighting energy consumption (LEC) were examined on West, South, East, and North zones of the target floors. In all the investigations, both techniques produced fairly the same outcomes. Figure 4.12, Figure 4.13, and Figure 4.14 present the SGEW, LEC, and TCL investigated on the West zone respectively.

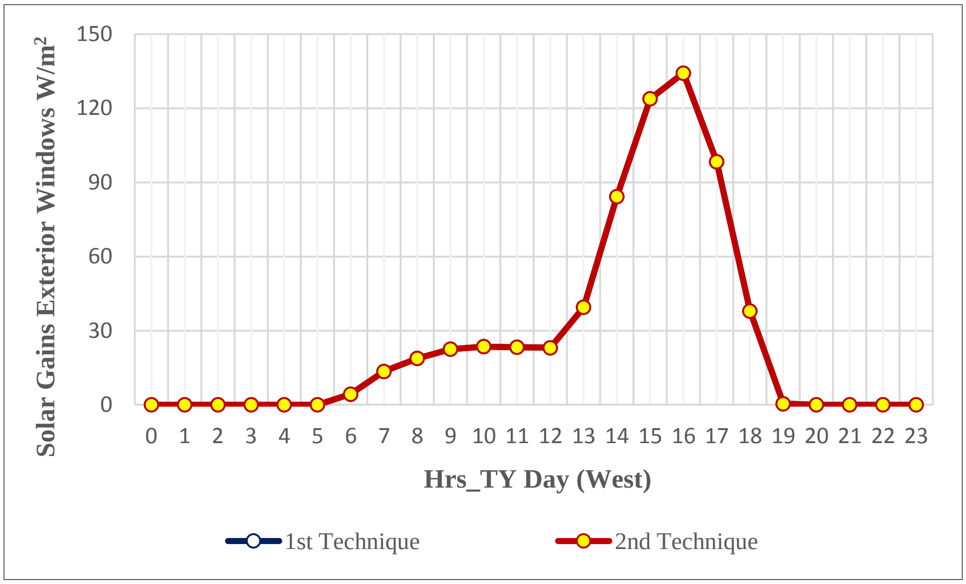


Figure 4.12 Solar Gains Exterior Windows W/m^2 (West)

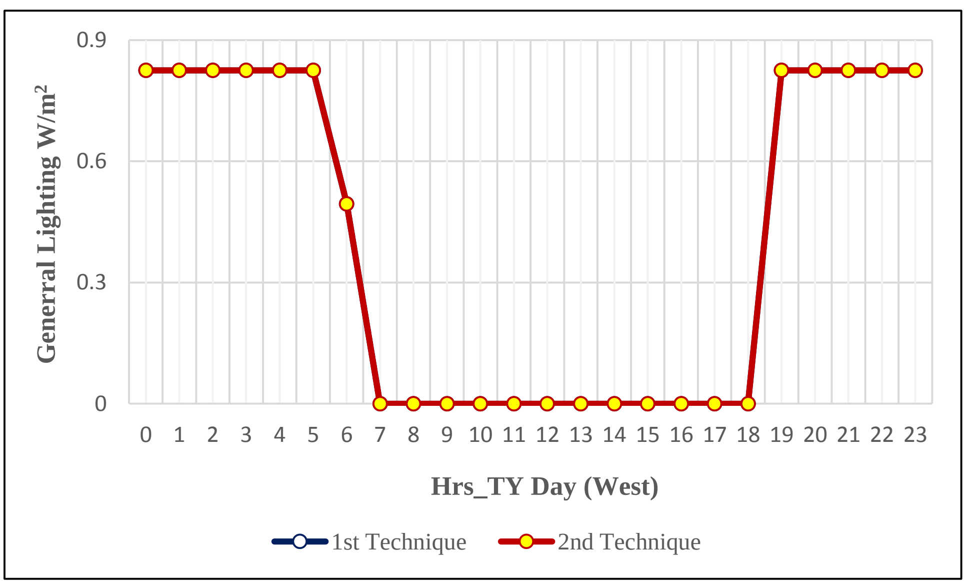


Figure 4.13 Lighting Energy Consumption W/m^2 (West)

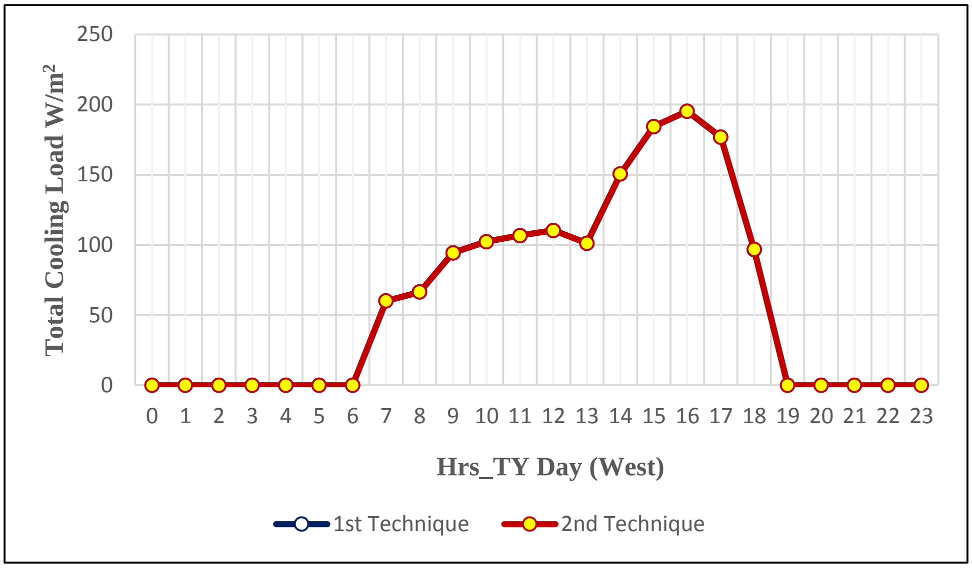


Figure 4.14 Total Cooling Load W/m^2 (West)

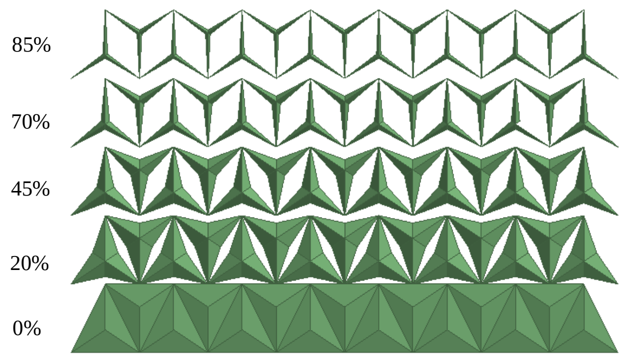
Table 4.1 explicitly explains the mode of operation of the 2 techniques. In the 1st technique, the operation schedule displayed in column 6 of Table 4.1 controls the operation of the dynamic shades. The curve on the operation schedule represents the sun path for a typical summer day on the west orientation. The transparency of the dynamic shades is displayed in column 4 as T. Therefore, between 00:00 - 04:00 hours and between 19:00 – 23:00 hours, the schedule allows the dynamic shades to transmit 85% of incoming solar radiation. 70% of incoming solar radiation is transmitted during the 5th and 6th hours of the day as well as 17th and 18th hours of the day. Furthermore, during the 7th and 8th hours as well as 15th and 16th hour, only 45% of incoming solar radiation is transmitted to the building envelope. 20% of solar radiation is transmitted at the 9th and 14th hours of the day. The operation schedule completely blocks all solar radiation between 10:00 – 13:00 hours of the day. The total SGEW obtained on the West zone throughout the day amounts to 647.8 W/m^2 and is recorded in the 2nd column of Table 4.1.

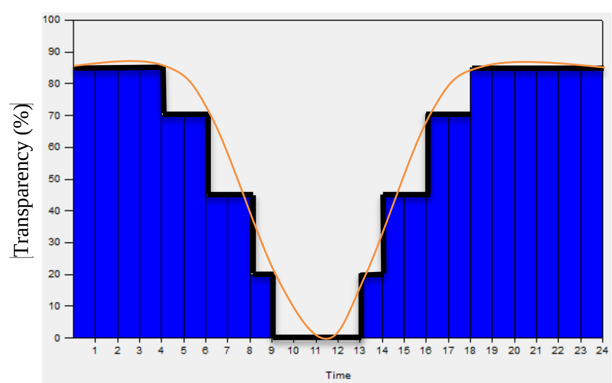
In the second technique where an operation schedule is not attached, the geometry is shown in the 6th column of Table 4.1 whereas the number of floor in which the geometry is attached is indicated in column 5. The operation schedule indicates that between 00:00 - 04:00 hours and between 19:00 – 23:00 hours, the 11th floor remains active and thus results were obtained from the West zone of the 11th floor. The 10th floor remains active between 05:00 – 06:00 hours and between 17:00 – 18:00 hours. Simulation results were gathered from the West zone of the floor for the active hours. Again, the 9th floor is active between 07:00 – 08:00 hours and between 17:00 -18:00 hours and results were obtained accordingly. At 9th and 14th hours, the solar radiation was recorded from the 8th floor. The 7th floor remains active between 10:00 – 13:00 hours and thus incoming solar radiation was obtained from the West zone of the floor. The summation of solar gain recorded from different floors for the day amounts to 647.8 W/m^2. Therefore, the 2 techniques produced the same results and thus offer alternatives to achieving *dynamic façade* in *DesignBuilder.* The same procedure was employed in examining SGEW, LCE and TCL on the West, South, East, and North orientations. However, only the procedure of obtaining SGEW on the West zone is explained in details here. The remaining Tables are illustrated in the appendix section from appendix A through appendix K for further reference purpose.

On the South zone of the building, the same results were obtained for SGEW and LEC. However, the 2nd technique showed 0.4% (4.2 W/m^2) increment in the TCE on the same zone. Figure 4.15 and Figure 4.16 illustrate the outcomes for SGEW and LEC respectively. The TCL on the South zone is illustrated in Figure 4.17.

Table 4.1 Solar Gains Exterior Windows W/m^2 (West)

Time	1st Technique	2nd Technique	T	Floor No.	Geometry & Operation Schedule
0	0	0	15%	11	
1	0	0	15%	11	
2	0	0	15%	11	
3	0	0	15%	11	
4	0	0	15%	11	
5	0	0	30%	10	
6	4.35265	4.35265	30%	10	
7	13.542	13.542	55%	9	
8	18.77999	18.77999	55%	9	
9	22.50867	22.50867	80%	8	
10	23.56779	23.56779	100%	7	
11	23.32486	23.32486	100%	7	
12	23.0957	23.0957	100%	7	
13	39.4929	39.4929	100%	7	
14	84.30096	84.30096	80%	8	
15	123.8056	123.8056	55%	9	
16	134.2361	134.2361	55%	9	
17	98.3251	98.3251	30%	10	
18	38.02835	38.02835	30%	10	
19	0.4761318	0.4761318	15%	11	
20	0	0	15%	11	
21	0	0	15%	11	
22	0	0	15%	11	
23	0	0	15%	11	
Total	**647.8368018**	**647.8368018**			





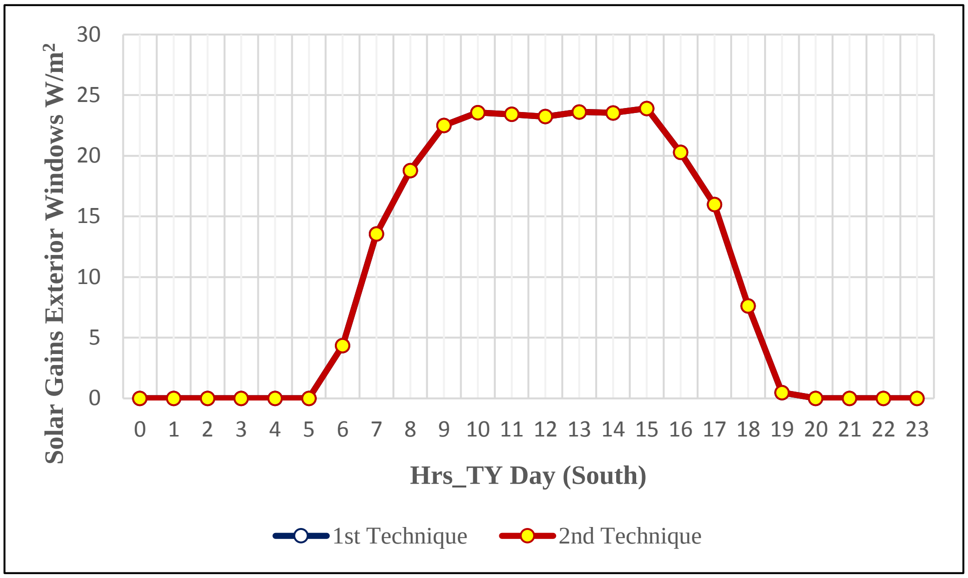


Figure 4.15 Solar Gains Exterior Windows W/m^2 (South)

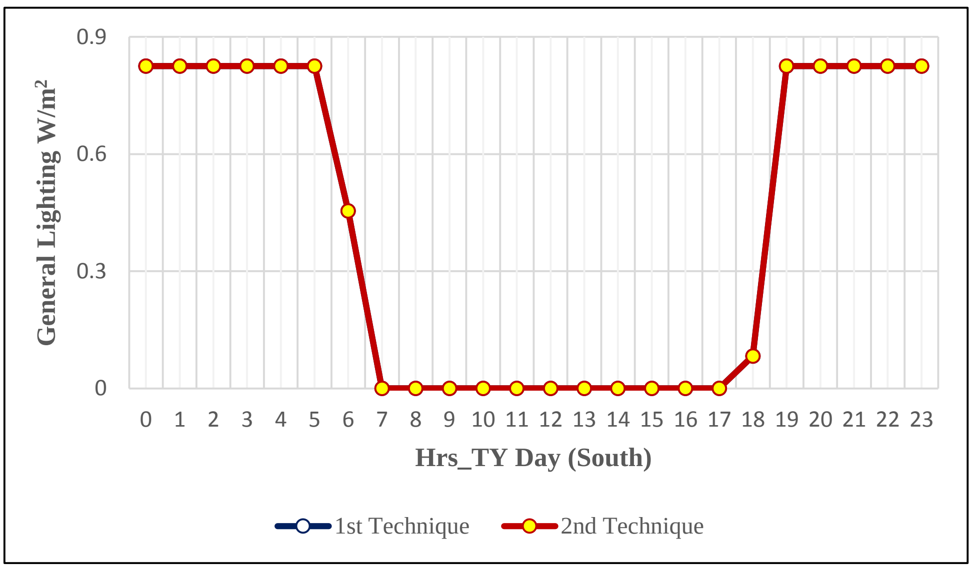


Figure 4.16 Lighting Energy Consumption W/m^2 (South)

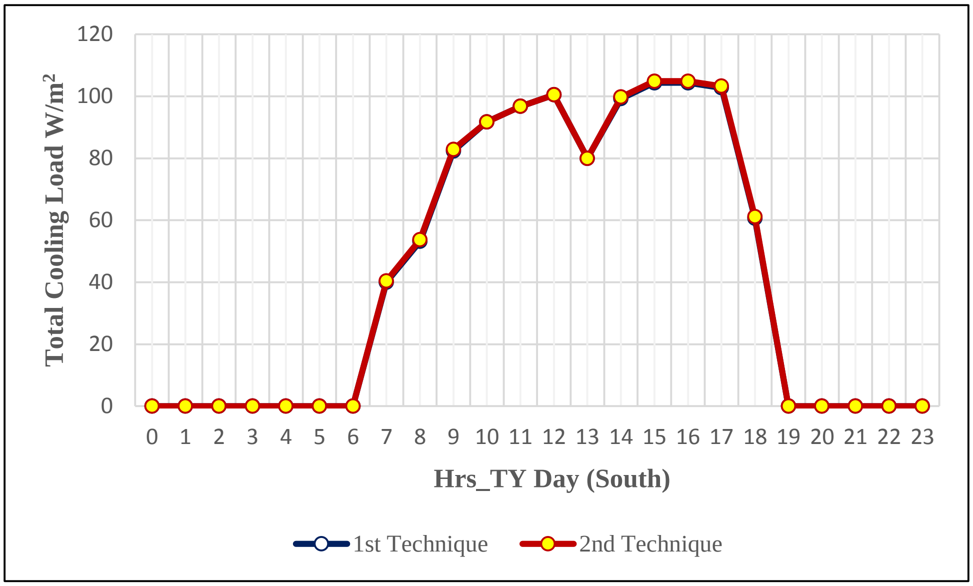


Figure 4.17 Total Cooling Load W/m^2 (South)

The 2 techniques were both efficient in all investigated areas on the East zone of the building. Both techniques produced the same outcomes for SGEW LEC, and TCE. Figure 4.18, Figure 4.19, and Figure 4.20 illustrate the outcomes for SGEW, LEC, and TCL respectively.

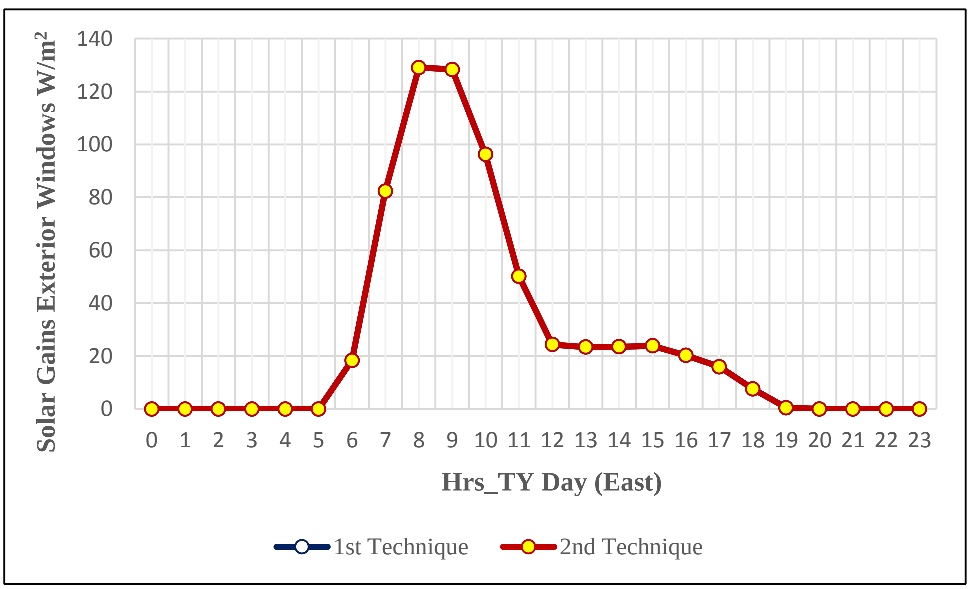


Figure 4.18 Solar Gains Exterior Windows W/m^2 (East)

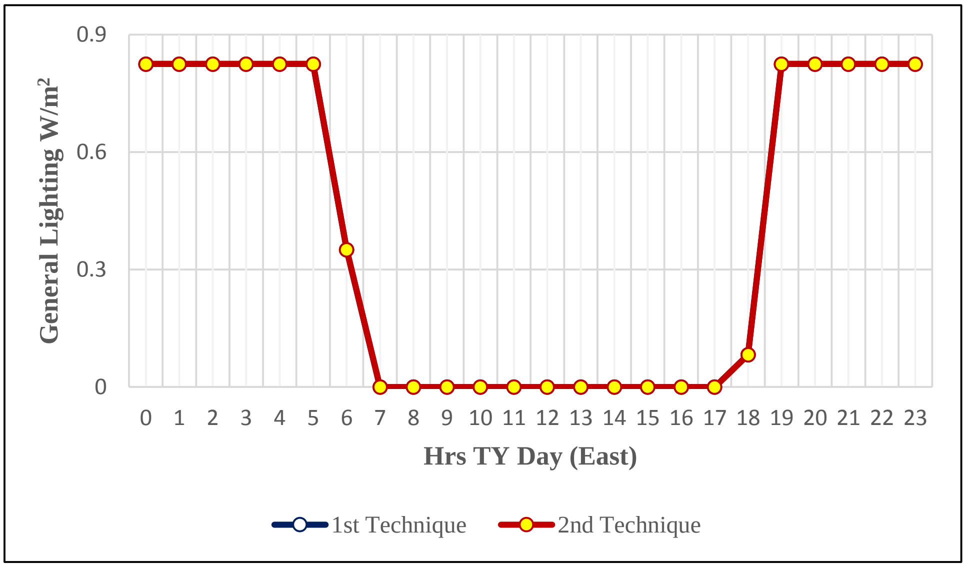


Figure 4.19 Lighting Energy Consumption W/m^2 (East)

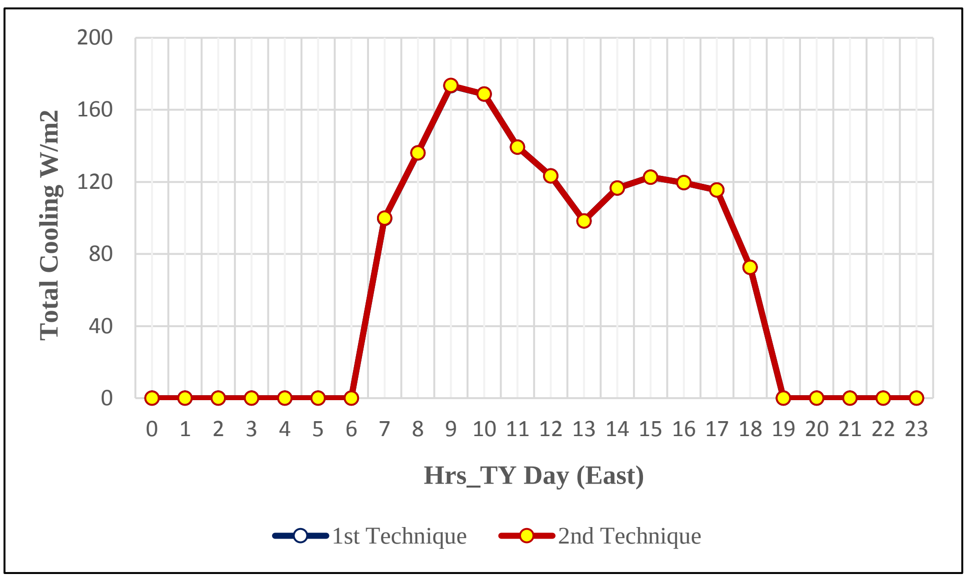


Figure 4.20 Total Cooling Load W/m^2 (East)

On the North zone of the building, the same results were realized for SGEW and LEC. However, the 2nd alternative consumed 0.36% (3.9 W/m^2) increment in the TCL on the same zone. Figure 4.21 and Figure 4.22 illustrate the outcomes for SGEW and LEC respectively. The TCL on the North zone is illustrated in Figure 4.23.

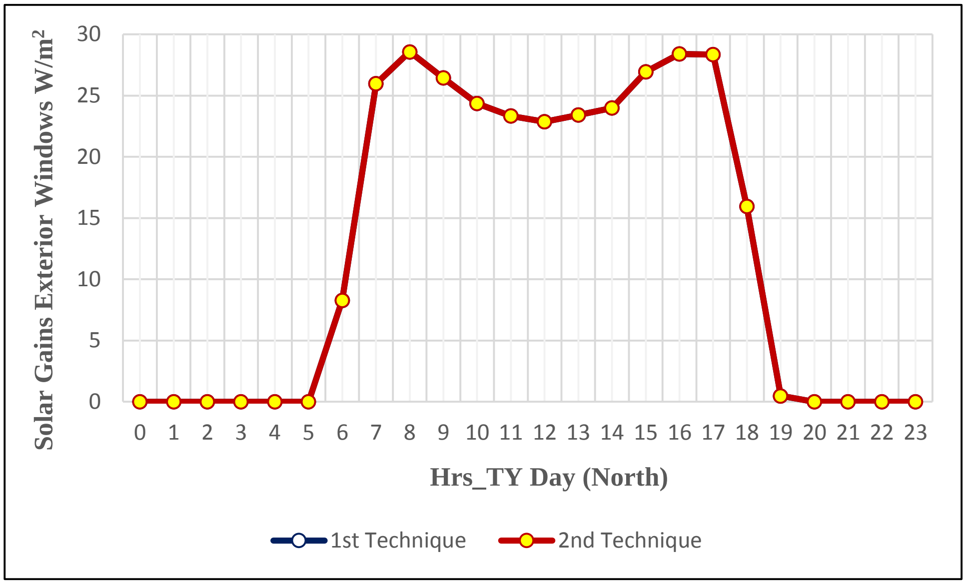


Figure 4.21 Solar Gains Exterior Windows W/m^2 (North)

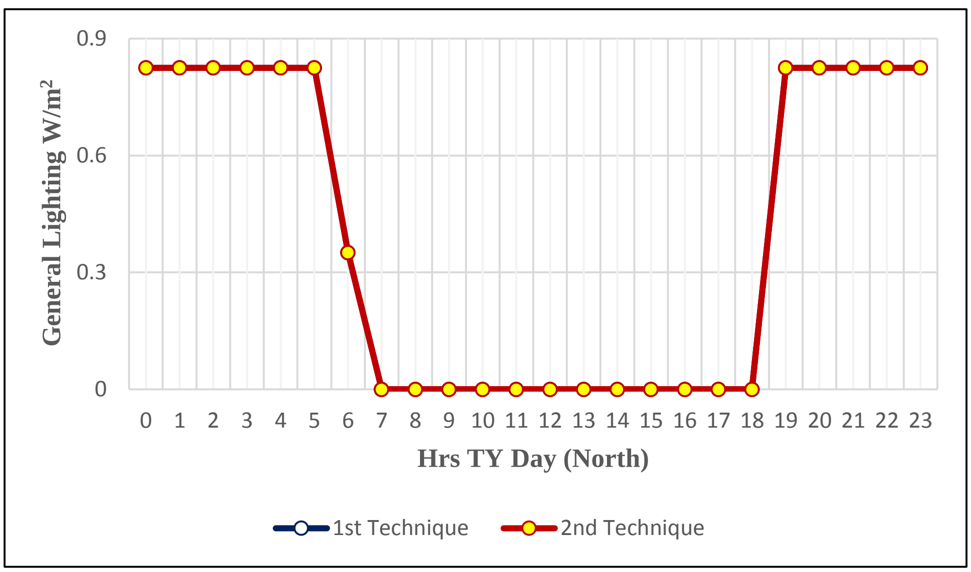


Figure 4.22 Lighting Energy Consumption W/m^2 (North)

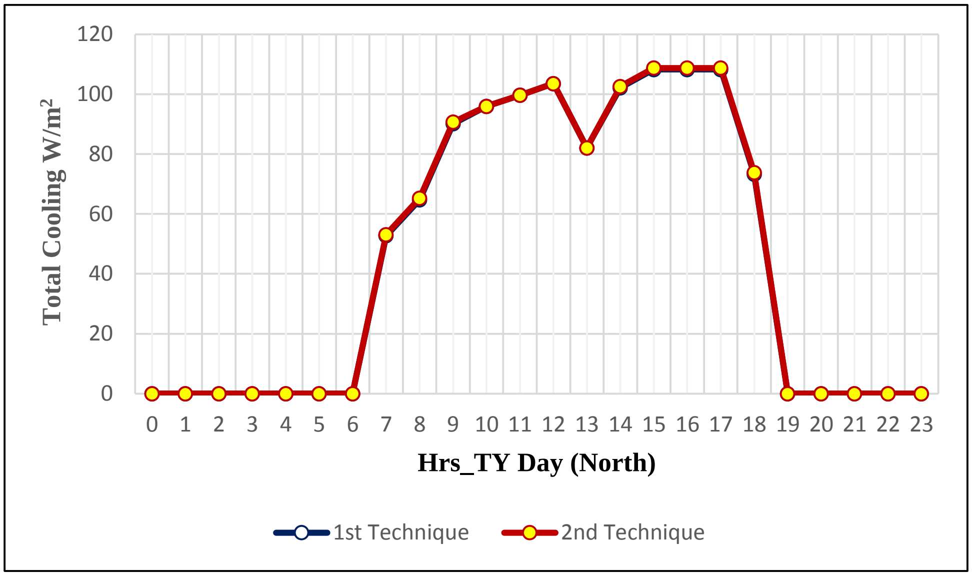


Figure 4.23 Total Cooling Load W/m2 (North)

4.2.4 Investigation of Actual Building Loads

Investigation of the actual SGEW and LEC when the dynamic shades are fully open throughout the day was conducted. The transparency of the dynamic shades was set at 85% throughout the day on all orientations for the investigation. Figure 4.24 illustrates the operation schedule of the dynamic shades. The investigation aimed at improving the performance of the dynamic shades by ensuring that the operation schedules conform to both zone and seasonal demands. A typical summer day was used for the exercise. High solar gain were recorded between 06:30 – 11:00 and between 13:30 – 18:00 on East and West zones respectively. The peak solar gains were recorded at 8:00 and 16:00 hours for East and West zones respectively. Therefore, operation schedules should be made to reduce the solar gains on East and West zones respectively. Low solar gains were recorded in South and North zones throughout the day. As such there is no concern in both South and North zones as low solar gains were observed throughout the day. Figure

4.25 presents the actual SGEW for all zones for an all-day fully open dynamic shades. Artificial lighting is only provided during occupied hours.

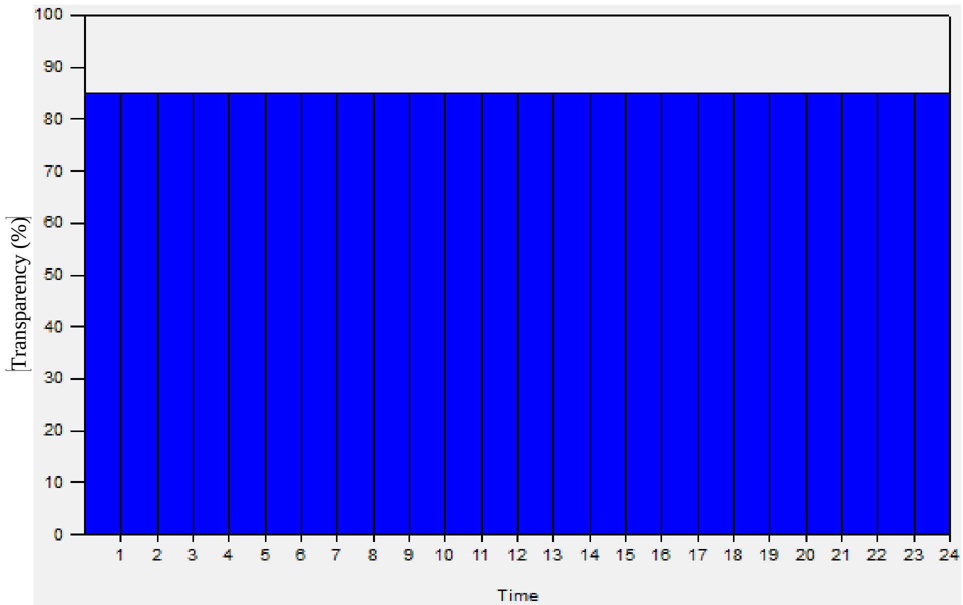


Figure 4.24 Operation Schedule of the Dynamic Shades

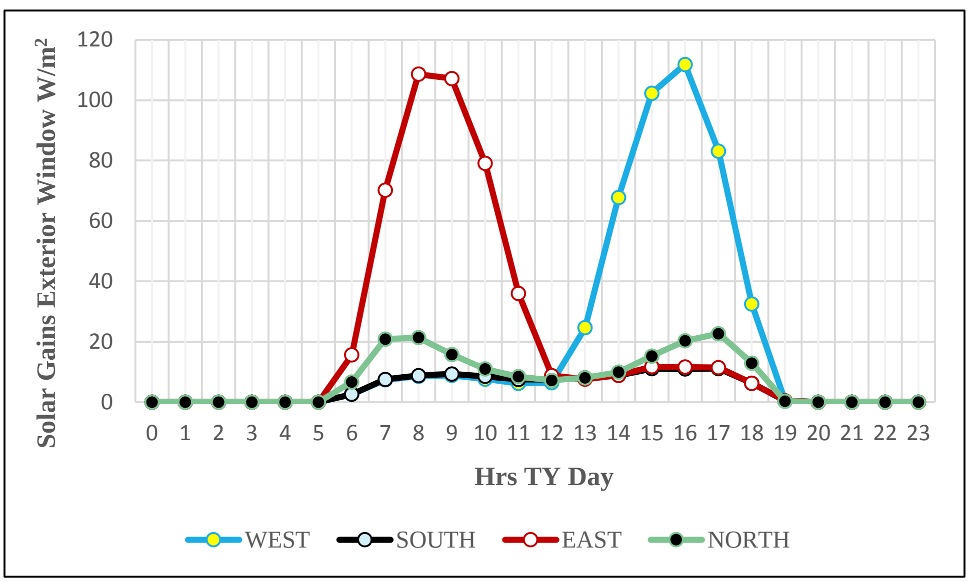


Figure 4.25 Solar Gains Exterior Windows W/m^2

Average LEC was recorded during most occupied hours. Higher LEC was observed in the late hours of the day (at 17:00 and 18:00 hours) when natural daylight is insufficient. Figure 4.26 illustrates the LEC for a typical summer day.

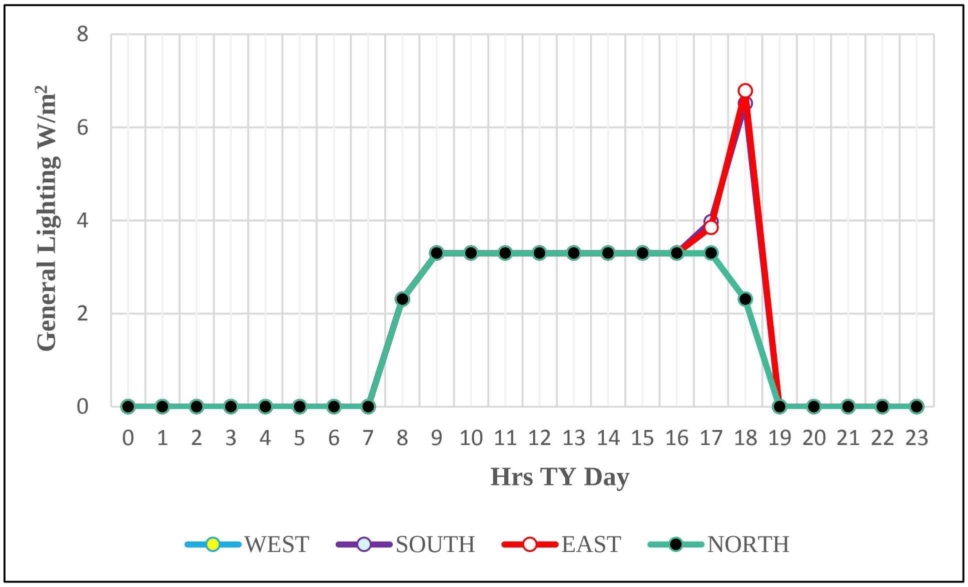


Figure 4.26 Lighting Energy Consumption W/m^2

4.2.5 Geometry Impact on Dynamic Façade's Performance

Investigations were carried out to determine the impact of geometry when it comes to dynamic façade's energy performance. Dynamic facade and a solid screen were investigated on a typical summer day. The transparency of both shading alternatives was set to 85% while 1 maximum transmission was utilized. The 2 alternatives were on 24/7 as no operation schedule was attached. SGEW and LEC have been investigated on all zones of the building. The same model was utilized for the investigation with the geometry of the shading elements being the only exception. Dynamic facade consumed 15.7% (84.6 W/m^2) less and 0.6% (0.2 W/m^2) less than *solid screen* for SGEW and LEC respectively on West zone. Figure 4.27 and Figure 4.28 illustrate the SGEW and LEC respectively on the West zone.

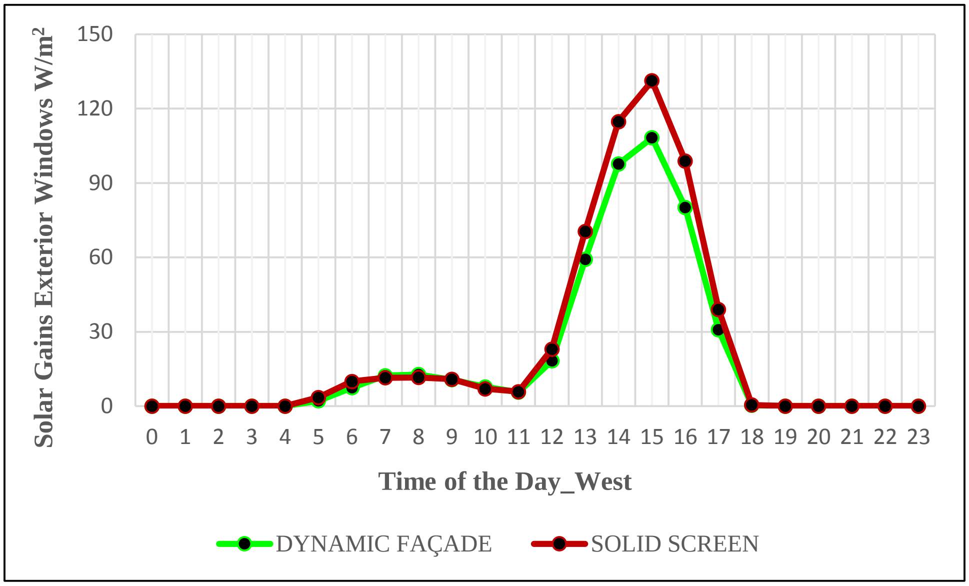


Figure 4.27 Solar Gains Exterior Windows W/m^2 (West)

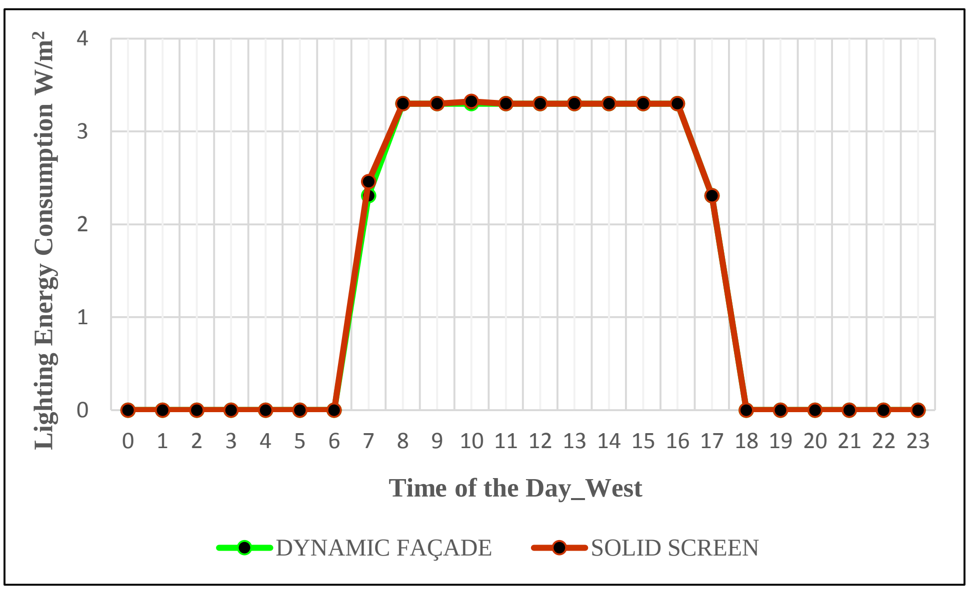


Figure 4.28 Lighting Energy Consumption W/m^2 (West)

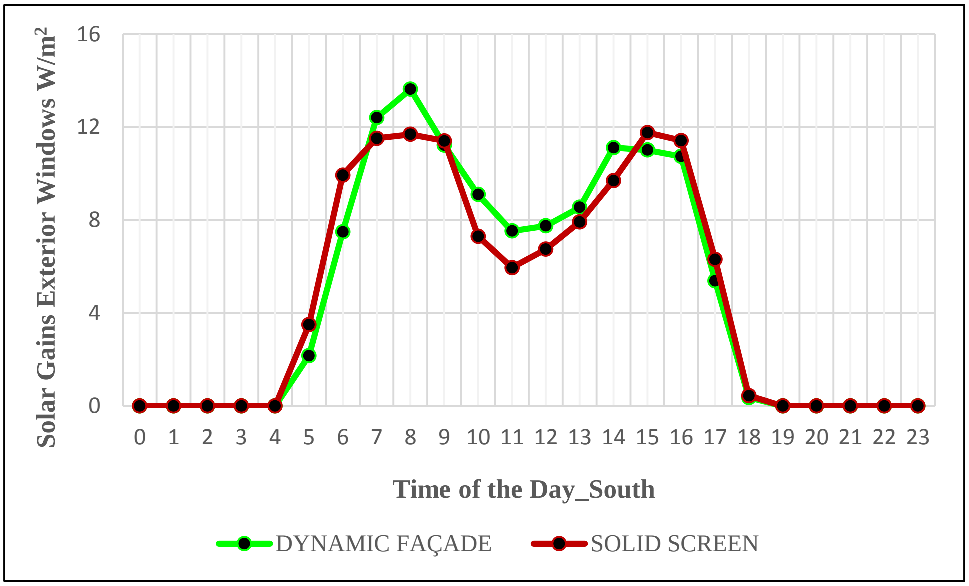


Figure 4.29 Solar Gains Exterior Windows W/m² (South)

Dynamic façade consumed 2.5% (2.9 W/m²) and 2.1% (0.8 W/m²) more SGEW and LEC respectively on the South zone than the solid screen. Figure 4.29 and Figure 4.30 depict SGEW and LEC on the South zone respectively. On the east zone, dynamic façade saved 14.9% (80 W/m²) SGEW than the solid screen.

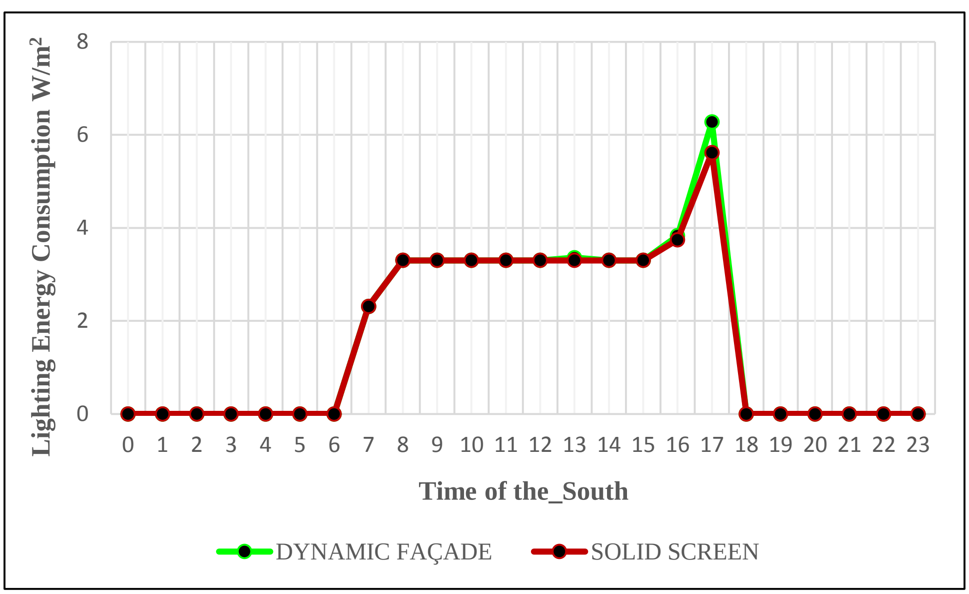


Figure 4.30 Lighting Energy Consumption W/m² (South)

However, dynamic façade consumed 2.4% (0.9 W/m^2) more LEC more than solid screen on the East zone. Figure 4.31 and Figure 4.32 show SGEW and LEC on the East zone respectively.

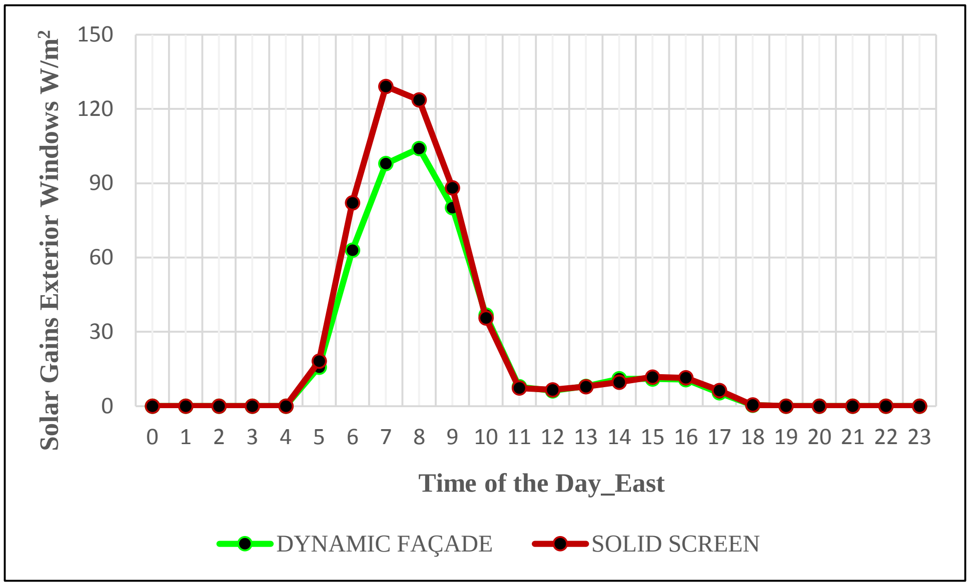


Figure 4.31 Solar Gains Exterior Windows W/m^2 (East)

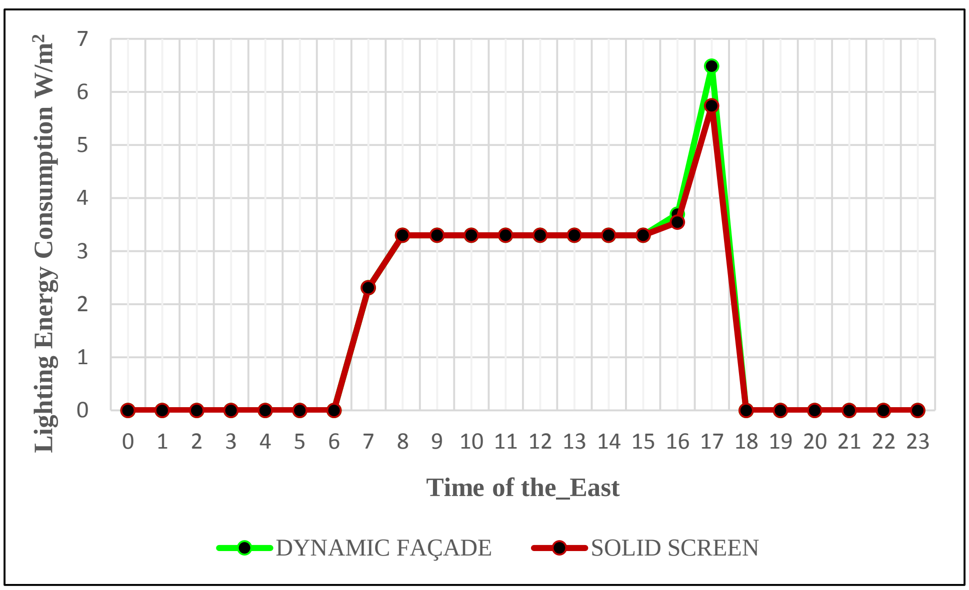


Figure 4.32 Lighting Energy Consumption W/m^2 (East)

Dynamic façade reduced SGEW on the North zone by 18% (32.6 W/m^2) compared to the solid screen. The reverse was the case when it comes to LEC. Dynamic façade consumed 2% more LEC (0.7 W/m^2) than the solid screen. Figure 4.33 illustrates SGEW observed in the North zone while LEC in North zone is shown in Figure 4.34. The impact of the investigated geometry of the dynamic façade has been observed to be more significant on all orientations except the South.

4.2.6 Configuring Dynamic Facades

Using different configurations, the impact of dynamic façade was investigated against a solid screen shading device. 2 samples from both dynamic façades and solid screen shading were examined on a typical summer day. The same operation schedule was applied where it is necessary.

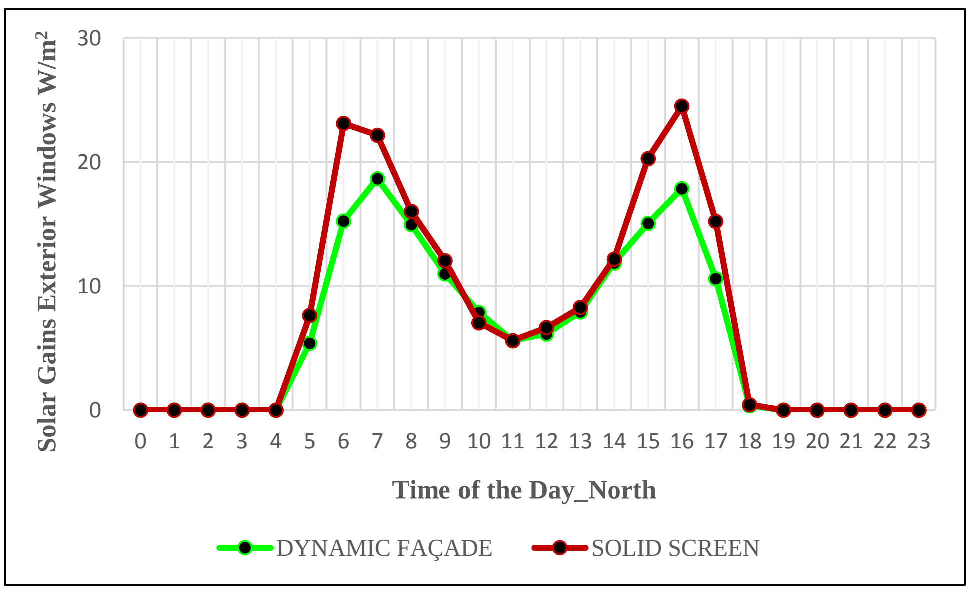


Figure 4.33 Solar Gains Exterior Windows W/m^2 (North)

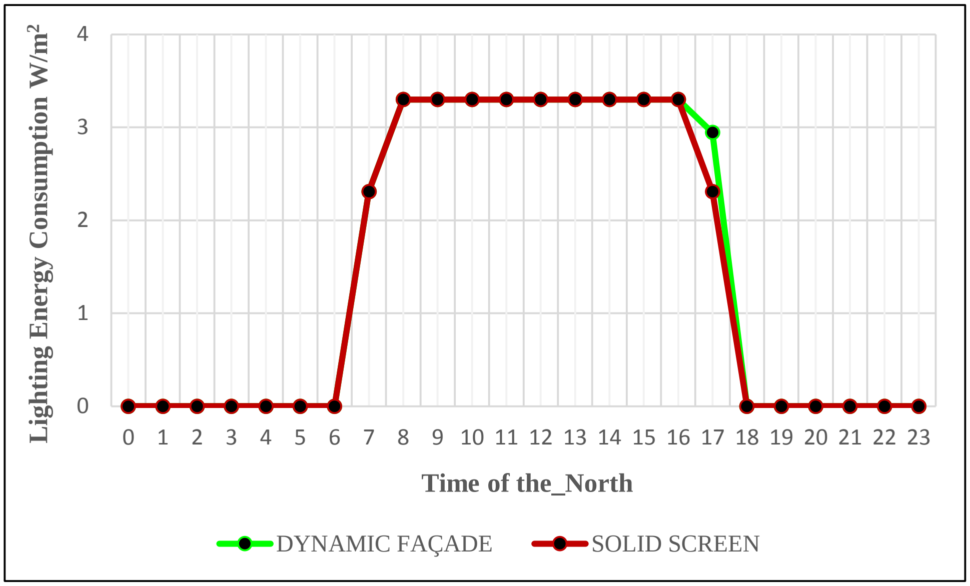


Figure 4.34 Lighting Energy Consumption W/m^2 (North)

Correct configuration is especially important in order to achieve the optimum performance from dynamic facade. The 4 examined samples were:

- Solid screen with 0 maximum transmission and no operational schedule attached (SS base case). This is regarded as the base case and comparisons were drawn upon.
- Solid screen with a maximum transmission of 1 and an attached operation schedule (SS schedule).
- Dynamic façade with a maximum transmission of 1 and an attached operational schedule (V0_DF).
- Dynamic façade with 0 maximum transmission and an attached operational schedule (V7_DF).

Solar Gains Exterior Windows (SGEW), Zone Sensible Cooling (ZSC), Lighting Energy Consumption (LEC), and Total Cooling Load (TCL) were investigated on the four examined cases. It was observed that only V7_DF allowed less SGEW than the base case. SS_schedule allowed more than 4 times SGEW while V0_DF allowed more than 2 times SGEW compared to the base case. V7_DF allowed 5.5% (5.7 W/m^2) less SGEW in to the building than the base case. Figure 4.35 depicts the performance of the investigated shading alternatives on SGEW. Again, SS_schedule had 41.1% (363.3 W/m^2) more ZSC whilst V0_DF achieved 9.8% (86.8 W/m^2) more than the base case. V7_DF achieved 8.7% (77.3 W/m^2) less ZSC compared to the base case. Figure 4.36 illustrates the ZSC for the investigated shading alternatives. Contrastingly, SS_schedule and V0_DF saved 70.6% (82.8 W/m^2) and 70.8% (83 W/m^2) lighting energy respectively compared to the base case. V7_DF consumed 4.5% (5.3 W/m^2) less lighting energy against the base case. Figure 4.37 presents the LEC analysis while TCL is illustrated in Figure 4.38. The TCL analysis summarizes the performance of the investigated shading alternatives. Overall, SS schedule and V0_DF consumed 39.5% (394.9 W/m^2) and 10.2% (102.1 W/m^2) more total cooling energy than the base case. V7_DF on the other hand consumed 0.6% (5 W/m^2) more TEC than the base case. Therefore, dynamic shades are more efficient in *DesignBuilder* with 0 maximum transmission and an attached schedule. V7_DF is more viable than the other 3 examined shading alternatives in this context. Table 4.2 summarizes the performances of the 4 examined shading alternatives on SGEW, ZSC, LEC, and TCL.

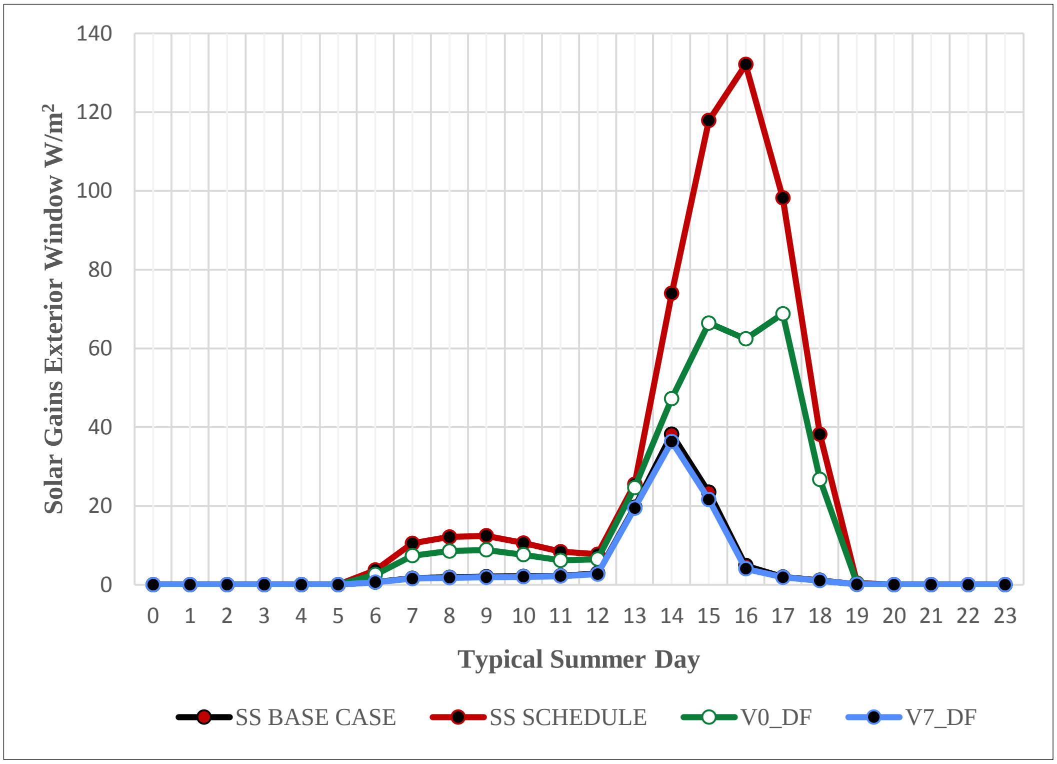


Figure 4.35 Solar Gains Exterior Windows W/m²

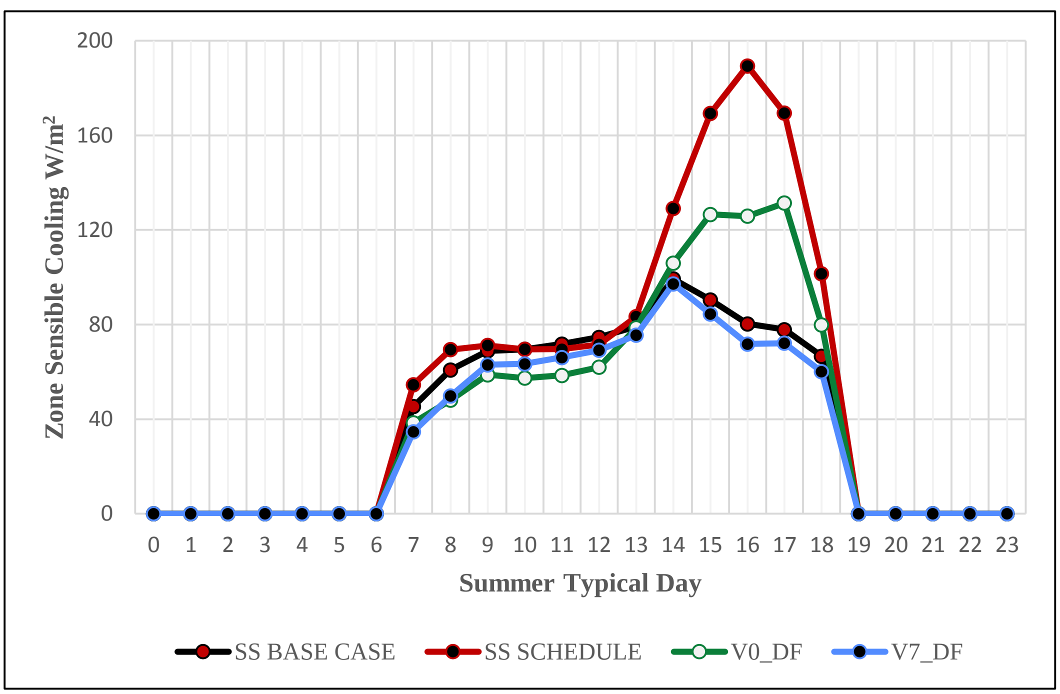


Figure 4.36 Zone Sensible Cooling W/m²

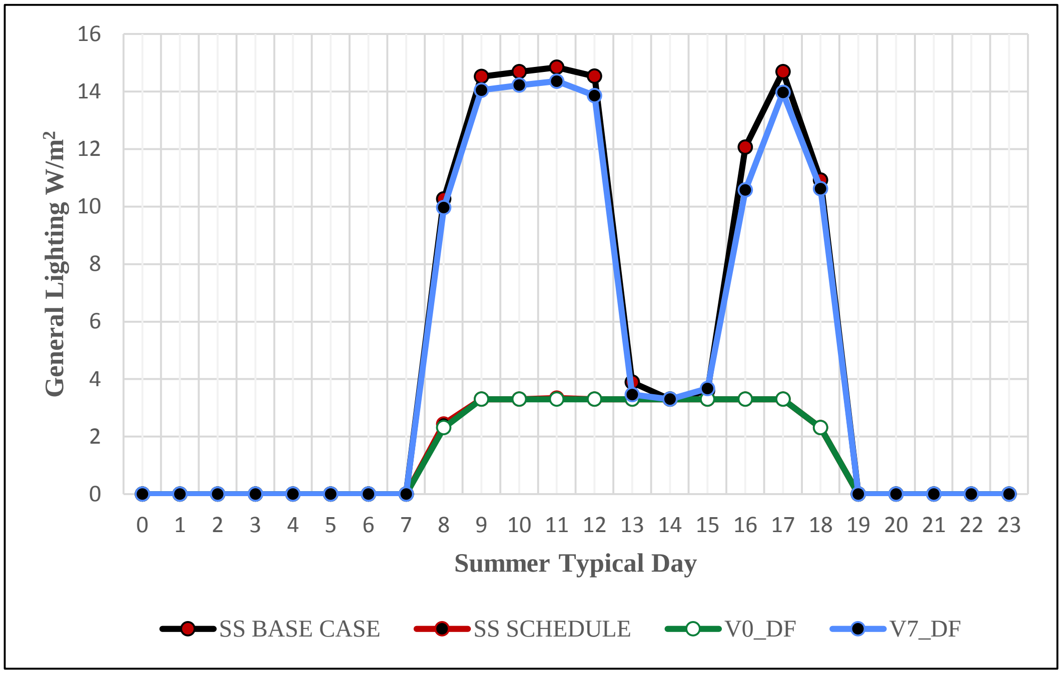


Figure 4.37 Lighting Energy Consumption W/m²

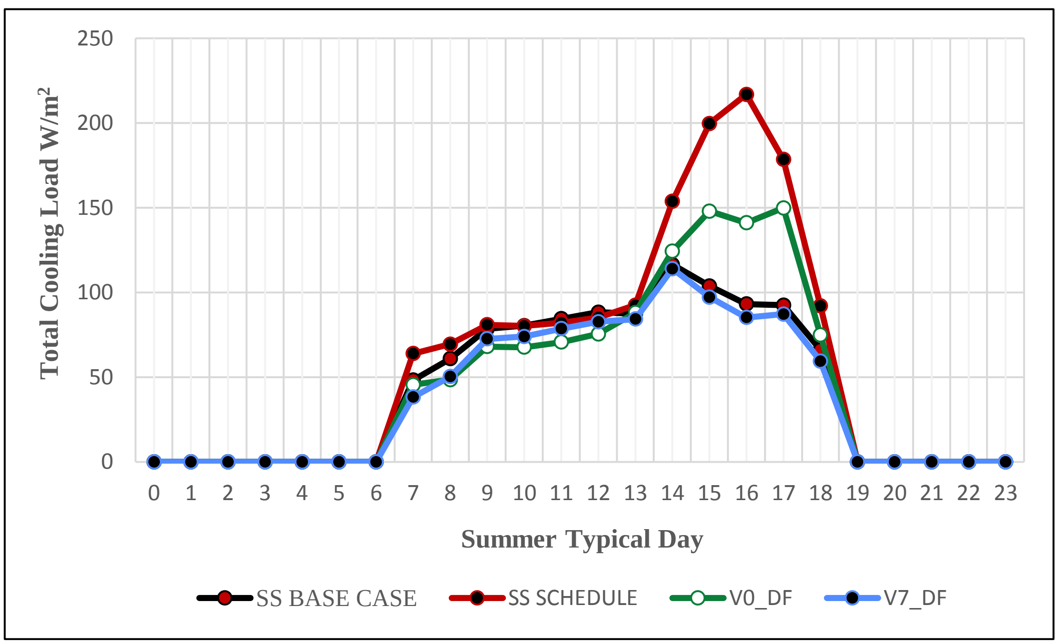


Figure 4.38 Total Cooling Load W/m²

Table 4.2 Performances of Alternative Shading Devices

Investigated Alternatives	**SGEW** (W/m^2)	**ZSC** (W/m^2)	**LEC** (W/m^2)	**TCL** (W/m^2)
SS Base case	**102.9**	**884.6**	**117.3**	**1000.1**
SS schedule	551.8	1247.9	34.5	1395
% difference	436.20%	41.10%	-70.60%	39.50%
V0_DF	344.30	971.40	34.30	1102.20
% difference	234.60%	9.80%	-70.80%	10.20%
V7_DF	97.2	807.3	112	923.7
% difference	-5.50%	-8.70%	-4.50%	-7.60%

4.2.7 Investigating the Impact of Dynamic Facades

In 4.2.6, different scenarios involving dynamic facade have been investigated. The best alternative for both solid screen (SS) and dynamic facades (DF) have been identified. SS performs best with 0 maximum transmission without any operational schedule attached. DF on the other hand performs efficiently when an operational schedule is attached with 0 maximum transmission. DF will perform more efficiently if the attached operational schedule satisfies both seasonal and orientation solar radiation requirements. Here, the performance of dynamic façade is compared against a non-shaded building option that is regarded as base case. Annual TCE was investigated on the West and South zones of a typical floor. The 2 zones were selected in order to assess the performance of dynamic facade in different orientations of the building. Again, the 2 zones selected are prone to high cooling loads in the building. Figure 4.38 presents the performances of dynamic facade on the West zone of a typical floor of the building. Dynamic façade saved 27.8% compared to the base case. The total floor area on the West zone across the 5 target floors is 960 m^2. Dynamic facade saves 63.9 kWh/m^2 annually. Overall, DF will save 61,344 kWh annually on the West zones of the target floors across the office building. The energy saving potential of dynamic facade presented in Figure 4.39.

In the south zone however, Dynamic façade saved only 17.4% of TEC compared to the base case. Dynamic façade realized 38.2 kWh/m^2 per unit meter. Therefore, across the South zones of the 5 floors dynamic facade saves 36,672 kWh/m^2. Figure 4.40 illustrates the performances of the investigated alternatives on the South zone of the target floor. The percentages of energy saving dynamic facade is equally shown.

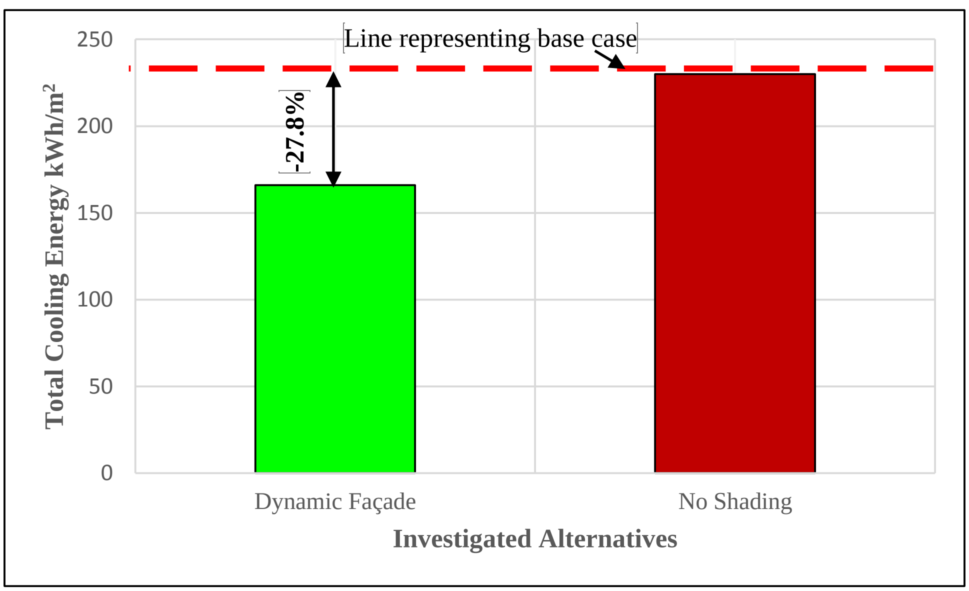


Figure 4.39 Annual Total Cooling Energy _ West

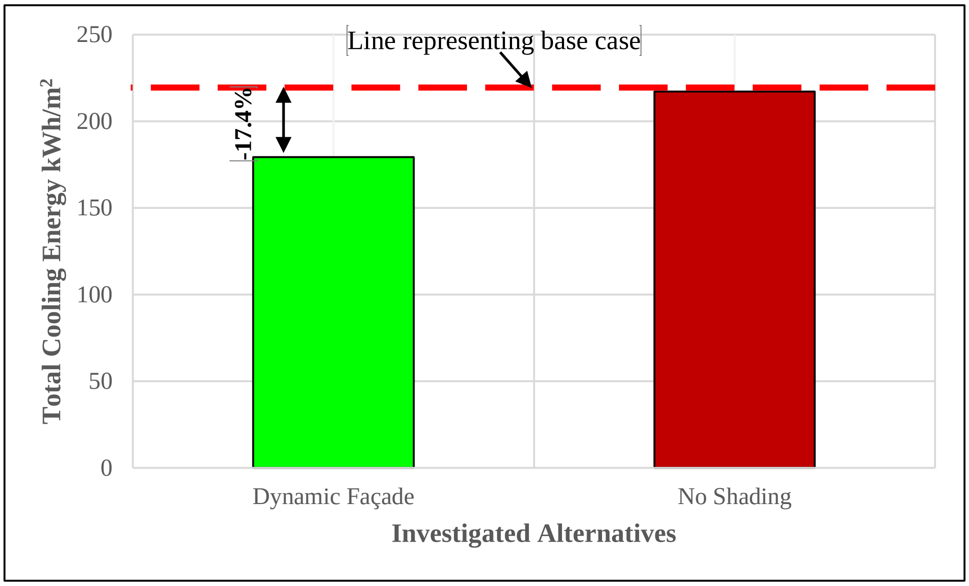


Figure 4.40 Annual Total Cooling Energy _ South

4.2.8 Positioning of Dynamic Façade

Placement of DF is important as that determines its performance. It is therefore important to determine the appropriate distance in which the DF should be situated away from the building envelope. In this regard, the DF's performance has been investigated at 1.5m, 1.0m, 0.5m, and even 0.0m away from the building envelope. This was conducted on both the West and South zones of a typical floor. This way, the appropriate distance of the investigated DF type is obtained for the two zones or orientations. Each zone of a typical floor has an area of 198 m^2. Therefore, each zone has an overall area of 960 m^2 across the target floors.

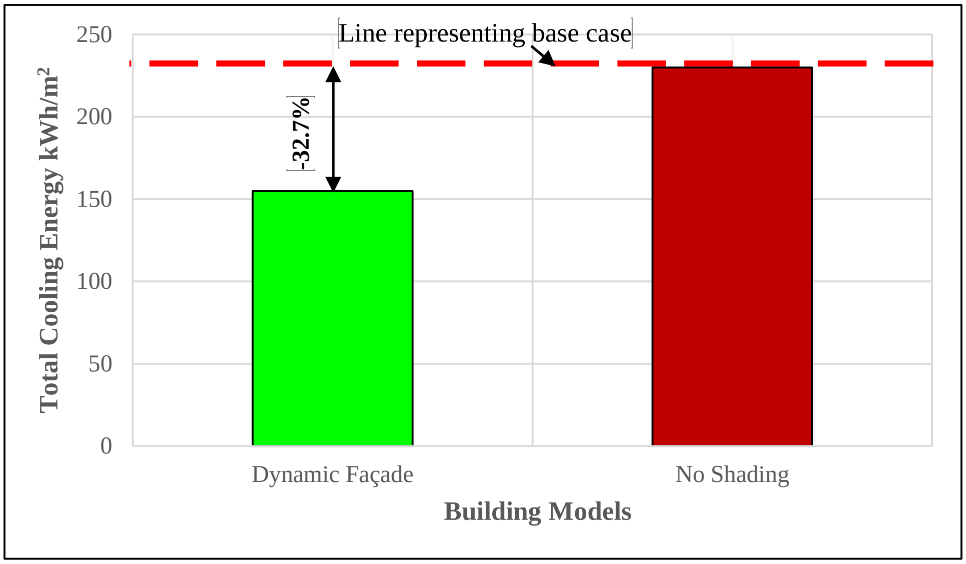


Figure 4.41 Annual Total Cooling Energy _ West (@ 1500mm)

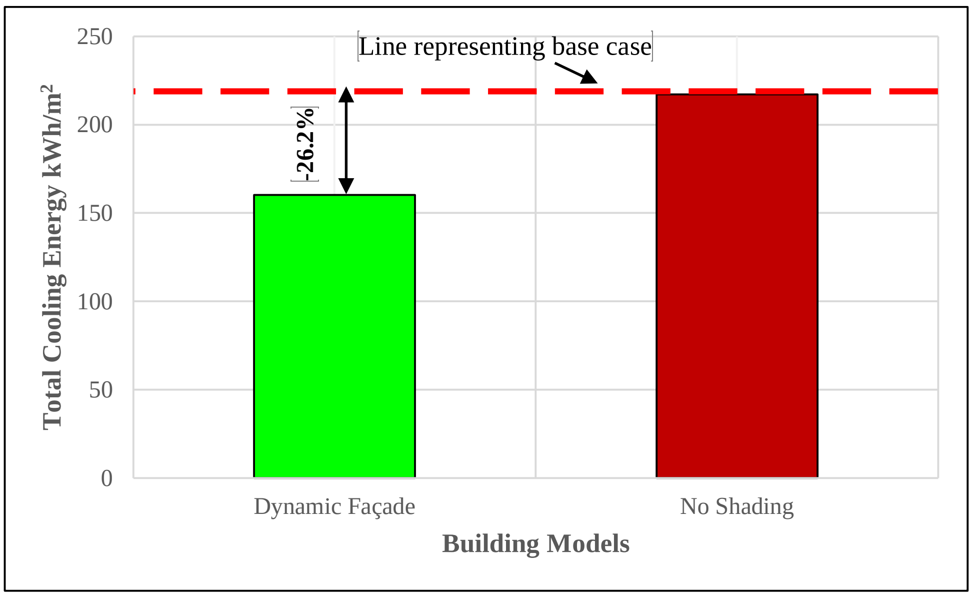


Figure 4.42 Annual Total Cooling Energy _ South (@ 1500mm)

The performances of dynamic façade has been investigated and reported at 1000 mm away from the building in 4.2.7. As such, only the distances of 1500mm, 500mm, and

0mm away from the building envelope will be reported here. Figure 4.41 presents the annual TEC of the investigated alternatives on the West zone at 1500mm away from the envelope. Dynamic facade saved 32.7% (75.1 kWh/m^2) compared to the base case. Therefore, if DF is employed, 72096 kWh will be saved annually on the West zone of the building compared to the base case. However, on the South zone, DF saved 32.2% of TEC (56.8 kWh/m^2) compared to the base case.

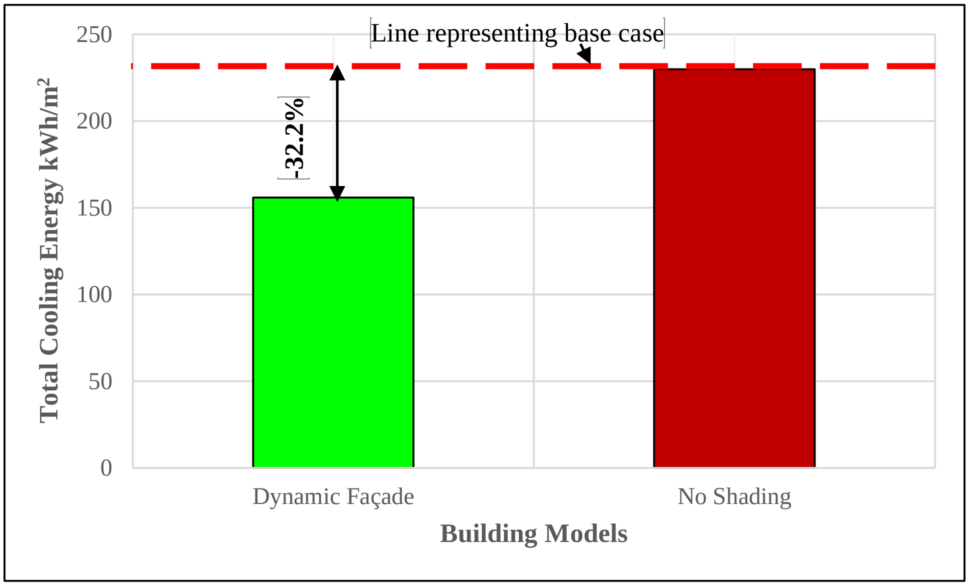


Figure 4.43 Annual Total Cooling Energy _ West (@ 500mm)

Overall, Dynamic facade consume 54528 kWh less of energy in maintaining optimal thermal comfort on the South zones of the 5 target floors. Figure 4.42 compares the performances of DF against the base case on the South zone at 1500 mm away from the building.

The efficiency of dynamic facade decreases as the distance between the dynamic facade and building envelope shortens. At 500mm away from the building envelope on the west zone, DF saved 32.2% (74 kWh/m^2) of TEC compared to the base case. Therefore, if DF is employed, 71,040 kWh will be saved on the West zone across the 5 floors compared to the base case annually. Figure 4.43 illustrate the performance of DF against the base case on the West zone. The (-) sign signifies energy savings.

On the South zone however, dynamic façade save 25% (54.2 kWh/m^2) while maintaining optimum thermal comfort in the zone. Overall, dynamic façade saves 52,032 kWh of energy in the South zones annually across the 5 floors. Figure 4.44 illustrate the dynamic façade on the South zones at 500mm.

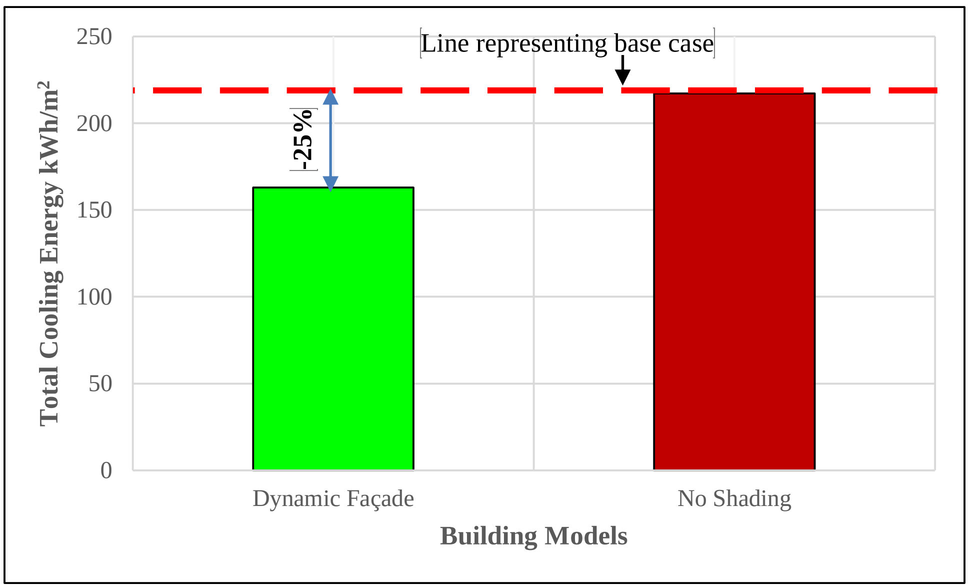


Figure 4.44 Annual Total Cooling Energy _ South (@ 500mm)

The next investigation involved placement of dynamic façade directly on the envelope surfaces to assess its impacts at 0mm away from the building. It could be recalled that *Flare* as discussed in case study 8 while reviewing literature acts in this same manner. Flare and other dynamic façades are more or less like a clothing material that is worn directly unto the desired building surface. On the West zone, dynamic façade recorded energy saving of 31.3% (72 kWh/m^2) for TEC compared to the base case.

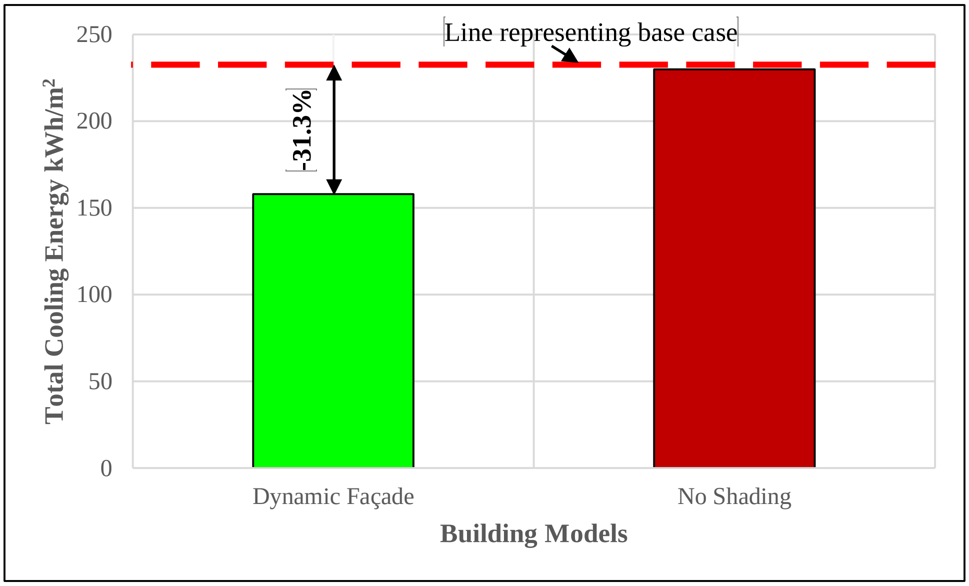


Figure 4.45 Annual Total Cooling Energy _ West (@ 0mm)

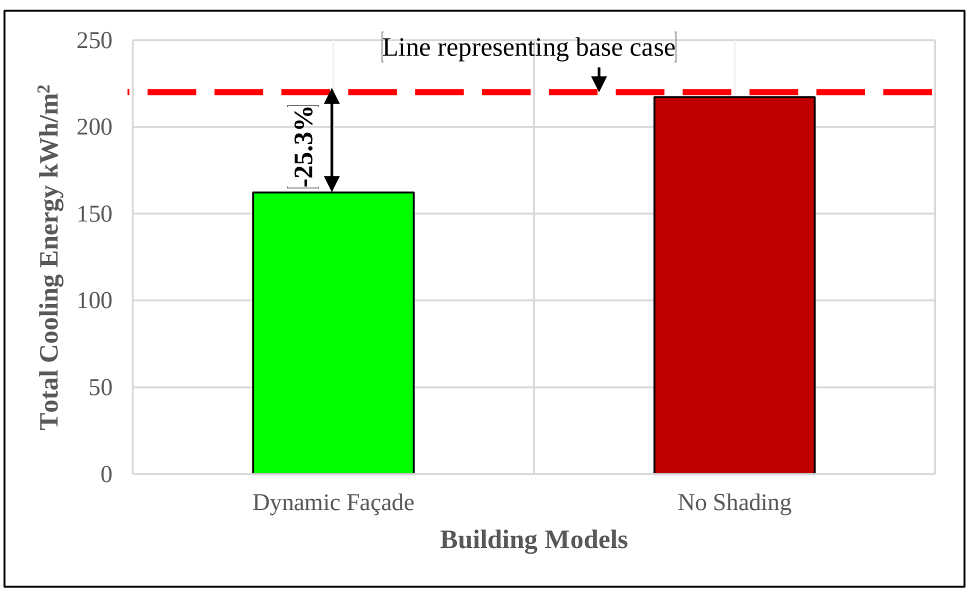


Figure 4.46 Annual Total Cooling Energy _ South (@ 0mm)

That is, if DF is to be employed, DF will save 69,120 Kwh annually in the West zones of the target floors. Figure 4.45 and Figure 4.46 graphically present the performance of DF at 0mm on the West and South zones respectively. On the South zone however, DF saved 25.3% (54.9 kWh/m^2) compared to the base case. Overall, DF saved 52,704 kWh in the South zones of the building compared to the base case.

It was observed that, the further away the DF is placed from the building, the better and improved its efficiency becomes to a certain degree. However, the best energy savings was recorded at 1000 mm away from the building rather than 1500 mm away from the building. There is no conclusive evidence to this outcome. Perhaps it could be due to the shadow that the DF is able to cast on the openings at 1000 mm but fail to do the same at 1500mm. The closer the dynamic façade is placed to the building envelope, the narrower the space becomes for air to circulate. This leads to the air being trapped within the space which will lead to heat transfer from the interior surface of the dynamic façade material to the building envelope through radiation.

4.2.9 Dynamic Façade and Building Orientation

So far in the course of this research, the investigations on the performance of DF has been conducted on the assumption that the building is at normal (right angle, 90^0). In reality however, most buildings are oriented at certain angles due to one reason or the other. In this section, the performance of DF is examined here and compared with the base case (the model with no shading). To execute this, the building was tilted from normal orientation (90^0) to 15^0 South_West (SW), 30^0 South_West (SW), and 45^0 South_West (SW) and the performance of DF was then examined in each case.

Annual investigations were categorized based on the examined building zones. In all tilted orientations on the West zone, DF saved more energy compared to the base case. DF saved 33.1%, 28.1%, 33%, and 35.5% at normal (90^0), 15^0 SW, 30^0 SW, and 45^0 SW respectively. The impact of DF in saving energy is effective irrespective of the building orientation. The best performance of DF on the West zone was observed at 45^0 SW (35.5%) while the least performance was recorded at 15^0 SW (28.1%).

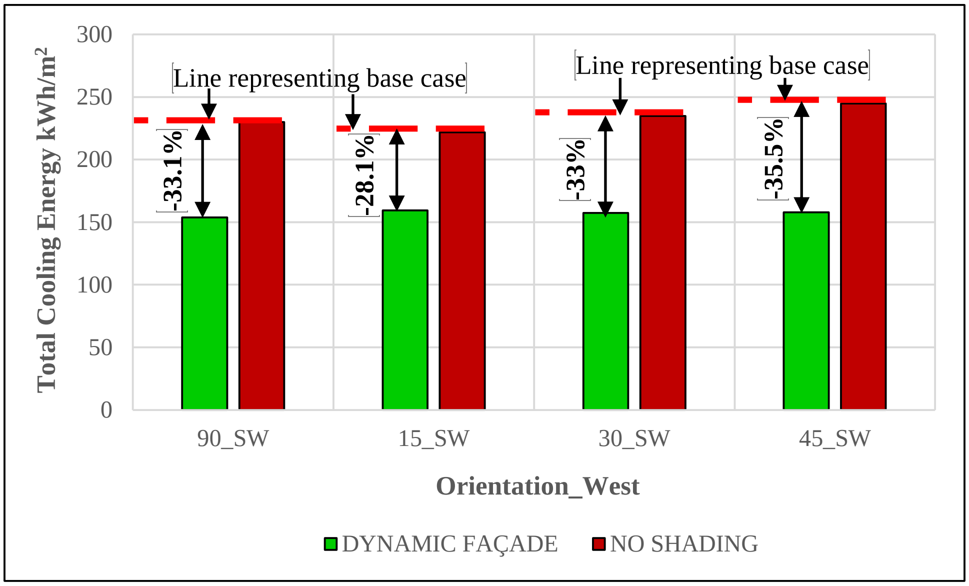


Figure 4.47 Annual Total Cooling Energy _ West

On the South zone, DF saves 26.9%, 34.2%, 34.9%, and 33.8% at normal (90^0), 15^0 SW, 30^0 SW, and 45^0 SW respectively. It was observed that DF performed more efficiently at 30^0 SW by saving 34.9% of TEC in the South zone. Figure 4.47 illustrates the annual TEC on the West zone for all orientations while Figure 4.48 depicts the same on the South zone.

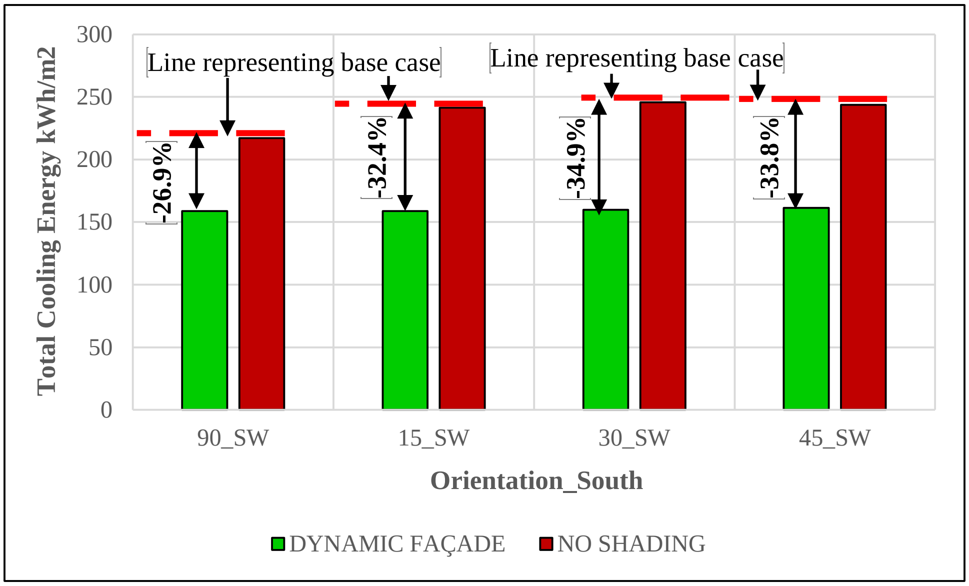


Figure 4.48 Annual Total Cooling Energy _ South

4.2.10 Performance of Dynamic Façade and Materials in *DesignBuilder*

In reality, the performance of a DF depends on the number and nature of materials as well as properties of individual elements that add up to form the composite DF. Materials properties such as thermal conductivity, solar absorptivity, material resistivity, arrangement and placement of materials among other factors determine the performance of a DF.

However, as a limitation in *DesignBuilder*, only a single material can be selected and examined as a DF. Another limitation of examining DF in *DesignBuilder* is that the user cannot decide the properties of the selected material. All investigations in this study have been conducted using polyvinylchloride (PVC) -tiles as the DF material. This section examines the energy conservation performance of 4 more materials of different nature alongside PVC-tiles. The selected materials were investigated at normal (90^0) and 1.0m away from the building envelope. The fact that these materials of varying properties produced exact annual total cooling energy on both West and South zones of a typical floor again reaffirm the another limitation of *DesignBuilder* in this regard. Table 4.3 presents the energy performance of examined DF materials on both West and South zones of a typical floor.

Table 4.3 Energy Performance of Dynamic Façade Materials

Examined Materials	**Type of Material**	**West zone (kWh/m^2)**	**South zone (kWh/m^2)**
Polyvinylchloride (PVC)	Plastics, Solids	153.7	158.7
Aluminum	Metals	153.7	158.7
Project component block material	Concrete	153.7	158.7
Extruded Polystyrene	Insulating material	153.7	158.7
Slate tiles	Tiles	153.7	158.7

4.3 Investigation to Determine the Best Hvac System

The first task involved examining the performance of relevant HVAC systems. This was to objectively select the best HVAC system to be used for the investigations on the real base case office building. According to the previous research, all-air VAV HVAC systems proved to be more efficient. As such, all all-air VAV HVAC systems alongside packaged HVAC system were investigated in *DesignBuilder*. For comparison purpose, all calibrations were kept constant and all the HVAC systems were investigated 1 after the other on an annual basis. The best energy efficient HVAC system from previous research is regarded as the real base case which consumes 206 kWh/m^2. The base case from previous research was VAV system (Cooling capacities and airflow auto sized) with variable speed drive as airflow control option. Table 4.4 shows the real base case alongside 7 investigated HVAC systems with their annual total cooling energy consumption in kWh/m^2. As Table 4.4 presents, VAV Air-cooled Chiller HR Outdoor air reset, and VAV Air-cooled Chiller HR Outdoor air reset + mixed mode, resulted in the least total cooling energy consumption. The 2 systems consumed 135.7 kWh/m^2 and 135.4 kWh/m^2 respectively. 4 other HVAC systems (VAV Air-cooled Chiller Fan-assisted Reheat (Parallel PIU), VAV Air-cooled Chiller Reheat, VAV Air-cooled Chiller Outdoor air reset, and VAV Dual duct Air-cooled Chiller) consumed 143.2 kWh/m^2 each while Packaged DX consumed 155.1 kWh/m^2 annually. In this regard, VAV Air-cooled Chiller HR Outdoor air reset + mixed mode is the most efficient HVAC system and will be regarded as the best overall base case. VAV, Air-cooled Chiller, Reheat was selected for analysis from the 4 sets of HVAC systems with the same efficiency. Figure 4.49 illustrates the comparison of the examined HVAC systems in reference to the best practice.

As Figure 4.49 graphically presents, the least energy saving was recorded with the usage of *Packaged DX* HVAC system which saves only 50.9 kWh/m^2 (24.7%) compared to the base case. The best energy efficient HVAC system (best overall base case) was *VAV, Air-cooled Chiller, HR, Outdoor air reset + mixed mode* which provided optimum thermal

Table 4.4 Investigated HVAC Systems.

Investigated HVAC systems	Annual total cooling (kWh/m^2)
VAV System (Cooling capacities and airflow auto sized) with variable speed drive as airflow control option (real base case)	206
Packaged DX	155.1
VAV, Air-cooled Chiller, HR, Outdoor air reset	135.7
VAV, Air-cooled Chiller, HR, Outdoor air reset + mixed mode	135.4
VAV, Air-cooled Chiller, Fan-assisted Reheat (Parallel PIU)	143.2
VAV, Air-cooled Chiller, Reheat	143.2
VAV, Air-cooled Chiller, Outdoor air reset	143.2
VAV, Dual duct, Air-cooled Chiller	143.2

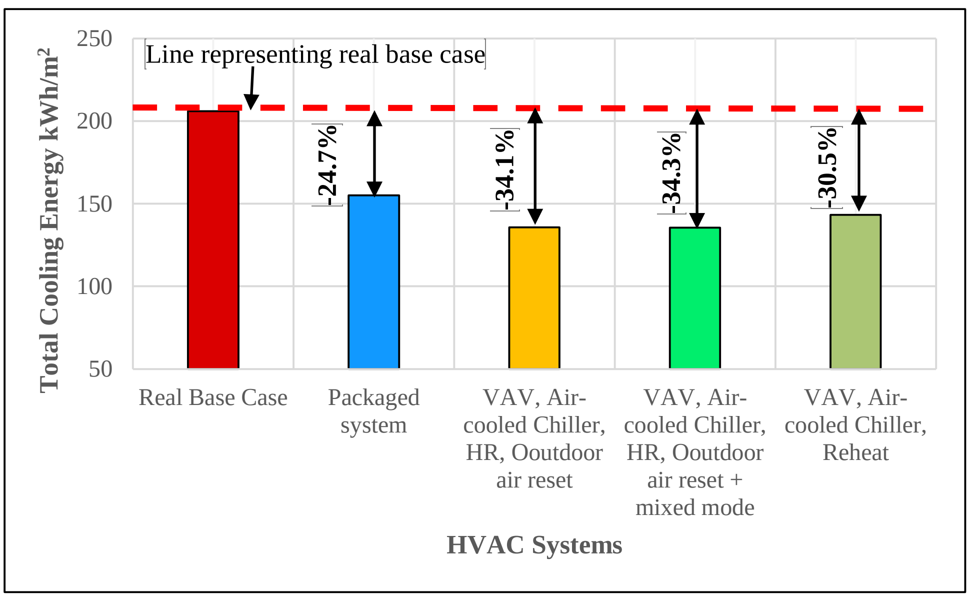


Figure 4.49 Performance of Evaluated HVAC Systems

comfort thereby saving 70.6 kWh/m^2 (34.3%). The two other alternatives, *VAV, Air-cooled Chiller, HR, Outdoor air reset* and *VAV, Air-cooled Chiller, Reheat* save 70.3 kWh/m^2 (34%). (34.1%) and 62.8 kWh/m^2 (30.5%) respectively. Therefore, *VAV, Air-cooled Chiller, HR, Outdoor air reset + mixed mode* is the best energy efficient HVAC system and is selected as best HVAC system for further investigation in the course of this research.

4.4 Investigating the Energy Performance of Dynamic Facades on Real Office Building

The energy performance of DF has been investigated on a theoretical office building so far in this research. Here, the energy performance of DF is examined on a real office building with an optimized HVAC system. 2 scenarios were investigated in this regard. Firstly, the energy performance of embedded or virtual shading devices in *DesignBuilder* was investigated. Secondly, the energy performance of DF was investigated. The examined DF mimics the mode of operation of *user-controlled dynamic facade* discussed in case study 1 (refer to chapter 2). All investigations were conducted on a real office building with the best HVAC system (that is, overall base case. Refer to 4.3). The investigations were carried out to determine the annual TEC of the entire real office building.

4.4.1 Investigating the Impact of Embedded Shading Devices

Embedded shading devices in *DesignBuilder* encompasses window shading systems. 4 types of window shading systems from the available ones in *DesignBuilder* were examined on the best practice model. Table 4.5 summarizes the performance of the examined window shading alternatives. It can be observed that the introduction of *Blind with medium reflectivity slats* to the best practice significantly reduces the annual total cooling energy from 135.4 kWh/m^2 to 123.2 kWh/m^2. This reduction accounted for 9% (12.2 kWh/m^2) reduction. The addition of *Shade role - medium translucent* equally reduces the total annual energy consumption by 4.8 kWh/m^2 (3.5%). However, it is observed that with the addition of *Drapes - open weave medium* and *Venetian blinds - medium (modelled as diffusing)* to the best overall base case the annual total cooling energy increases to 137.8 kWh/m^2 and 136.5 kWh/m^2 respectively. This increase in annual total cooling energy consumption lead to 2.4 kWh/m^2 (1.8%) and 1.1 kWh/m^2 (0.8%) respectively. Figure 4.50 compares the performance of embedded shading devices to the best overall base case. Figure 4.50 also illustrates the percentage differences (decrease or increase) compared to the best overall base case only. Therefore, the best performance is obtained with the usage of *Blind with medium reflectivity slats* on the best overall base case.

Table 4.5 Performance of examined Embedded Shading Devices

Best Practice + Embedded Shading Devices	Annual Total Cooling Energy (kWh/m^2)
Best overall base case only	135.4
Best overall base case + Drapes - open weave medium	137.8
Best overall base case + Shade role - medium translucent	130.6
Best overall base case +Venetian blinds - medium (modelled as diffusing)	136.5
Best overall base case + Blind with medium reflectivity slats	123.2

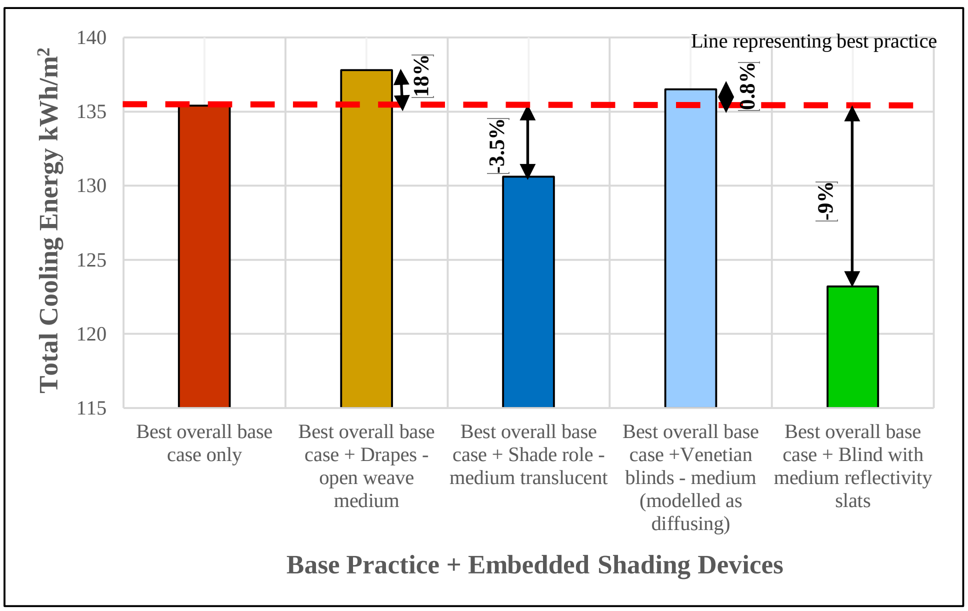


Figure 4.50 Performance of Embedded Shading Devices on Best Overall Base case.

4.4.2 Investigating the Impact of Dynamic Facades

The introduced *window shading system* on the best overall base case was replaced with a dynamic façade. This was to examine the impact of dynamic façade on the best overall base case and draw comparisons with embedded shading systems. The performance of the dynamic façade on the best overall base case is compared with that of the embedded shading systems. The introduction of DF to the best practice significantly reduces the annual total cooling energy from 135.4 kWh/m^2 to 110.3 kWh/m^2. This reduction in energy consumption accounted for 18.5% (25.1 kWh/m^2). The building has a total occupied floor area of 6,376.8m^2. DF saves 160,057.68 kWh out of 863,418.72 kWh consumed by the best overall base case. Therefore, if DF is employed, almost one-fourth of the total energy consumption will be reduced. This is because DF is only applied to the South, East, and North orientations of the building but yet 18.5% energy saving was realized. The West orientation was overlooked due to its smaller size of openings. Also, DF saved more than twice of the energy saving recorded by the embedded shading elements (i.e. 18.5% against 9%).

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This research has been conducted in various phases in order to achieve the desired objectives. In its initial stage, extensive literature review was conducted to determine the status of energy usage in buildings in hot climates. It was evidently observed that buildings consume high percentage of the total energy utilized in hot climates. In buildings, HVAC systems use the major portion of this energy, accounting for about 72% of the total electricity utilized in buildings (for instance in KSA). In an attempt to reduce the amount of energy utilized in office buildings especially, energy conservation strategies in office buildings were reviewed from practical case studies. The concept of dynamic facades was thoroughly and comprehensively reviewed in which 16 case studies where dynamic facades were utilized in real life were analyzed and presented. Matrix and guidelines for appropriate selection of dynamic façade was developed therefrom.

This research is a continuation of a previous research that optimized the HVAC system of an office building. The office building with an optimized HVAC system is located in hot climates of Al-Khobar, KSA and was selected as the case study (real base case). A review in to the state-of-the-art available Building Energy Simulation (BES) tools revealed that *DesignBuilder* is most appropriate to handle the challenges of modeling and simulating of both the theoretical base case and the real base case office buildings.

Modeling the real base case consists of site inventory, AutoCAD utilization, and *DesignBuilder* involvement. The best energy efficient HVAC system was identified and adopted for the investigations conducted. A flow chart was developed which summarizes a detailed procedure involved in modelling a dynamic façade in *DesignBuilder*. The flow chart also demonstrated how to examine the energy performance of a dynamic façade.

The energy performance of dynamic façade was investigated, analyzed, and compared with a base case model that has no attached shading of any kind. All investigations carried out were grouped into 3 major categories. The first category examined the determined the energy performance of dynamic facade on a theoretical base case office building. Secondly, investigations were conducted to determine the best HVAC system. Finally, the energy performance of dynamic façade was examined on the best overall real base case office building. Table 5.1 summarizes all examined scenarios regarding the energy performance of dynamic façade in this research. The table describes all conducted investigations, compares the energy performance of dynamic façade to a non-shaded (base case) building model.

From Table 5.1, the workability of DF was first confirmed in *DesignBuilder*. The energy performance of DF on a sample office model against the same non shaded building model ranges from 23.1% through 33.4%. The energy performance of dynamic façade was observed to be orientation dependent as it is more effective on the western and eastern orientations compared to the southern orientations. Similarly, the impact of geometry has been observed to be more significant on western and northern orientations. Therefore geometric impact of shading devices is orientation dependent. Also, DF tends to be more effective when positioned near the building envelope. That is, the closer a dynamic shade is placed, the higher becomes its efficiency. Although there are certain identified limitations with *DesignBuilder* regarding the calibration and simulation of DF, dynamic façade accomplished an energy savings of 18.5% at 800mm away from the building envelope compared to 9% saved by embedded shading devices against a performing static facade.

Now, comparing the energy performance of dynamic facades recorded in this research and that of real dynamic facades discussed in the literature review, a maximum energy saving potential of 33.4% has been recorded compared to Kacinalis C. et al. that achieved an energy savings of 15-18% experimentally. Therefore the energy performance of dynamic façade recorded in this research is more efficient that what was reported in the literature. In existing case studies reported in the literature however, a maximum energy savings of 50% was realized by the dynamic honeycomb façade of Al-Bahr for example. This difference between energy savings recorded in real building and that achieved in this research may be due to the identified limitations reported in 5.1. In this regard, recommendations have been suggested to BES tool's producers and *DesignBuilder* in particular. Overall, this research has proved how efficient and vital is dynamic façade when it comes to energy saving while maintaining thermal and visual comfort in buildings. This shows how significant is the energy efficiency of dynamic facades. Dynamic façades can play a critical part in energy efficient building envelope design. The research concludes with a set of recommendations to help improve the modelling, configuration, and simulation of dynamic facades in *DesignBuilder* and other Building Energy Simulation (BES) tools.

Table 5.1 Summary of Results

Description of Investigation	Energy saving of DF against TBC
Workability of dynamic façade in *DesignBuilder* (Daily TCE for a summer typical day)	
East	-52.3%
West	-47.7%
Annual Total Cooling Energy (TCE) typical floor	-34.9%
Impact of shading devices on load parameters (West zone)	
SGEW	-86.3%
ZSC	-49.6%
LEC	200
Geometry Impact of Dynamic façade's performance (typical summer day)	Energy saving against Solid Screen
SGEW _ west zone	-15.7%
LEC _ west zone	-0.6%
SGEW _ south zone	2.5%
LEC _ south zone	2.1%
SGEW _ east zone	-14.9%
LEC _ east zone	2.4%
SGEW _ north zone	-18%
LEC _ north zone	2%
Impact of dynamic façade	
Annual TCE at 1500mm away from the building	
West zone	-32.7%
South zone	-26.2%
Annual TCE at 1000mm away from the building	

West zone	-33.1%
South zone	-26.9%
Annual TCE at 500mm away from the building	
West zone	-32.2
South zone	-25
Annual TCE at 0mm away from the building	
West zone	-31.3
South zone	-25.3
Dynamic Façade and Building Orientation	
Annual TCE (West orientation)	
at 90^0 South _ West	-33.1
at 15^0 South _ West	-28.1
at 30^0 South _ West	-33
at 45^0 South _ West	-35.5
Annual TCE (South orientation)	
at 90^0 South _ West	-26.9
at 15^0 South _ West	-34.2
at 30^0 South _ West	-34.9
at 45^0 South _ West	-33.8
Energy Performance of Dynamic Façade on Real Office (Adopted case study)	**Energy saving of DF against RBC**
Best overall base case.	Real base case.
Best overall base case + Embedded shading devices	9% energy savings.
Best overall base case + Dynamic Façade at 800mm away from envelope	18.5% energy savings.

5.1 Limitations and Recommendations

The energy performance of dynamic facade has been successfully investigated. However, it was not without certain limitations. A set of recommendations are hereby suggested alongside the identified limitations. Further research into the field of dynamic facades is also recommended.

Solar radiation has been observed to be an important parameter in determining the cooling load in a building. It is an essential factor that is considered to be one of the control types for embedded shading devices in *DesignBuilder*. As a control type, solar radiation can either be *direct normal*, or *ground horizontal*. These types of solar radiation have different behavior and affect the cooling load of a building differently. When used as a control type, direct normal and ground horizontal have different direct impact on the Solar Gains Exterior Windows (SGEW) and the entire total cooling load of a building. Similarly, dynamic façade will react differently to direct normal and ground horizontal solar radiations accordingly. It is therefore important to know which type of solar radiation the user is dealing with when it comes to dynamic facade investigations in *DesignBuilder*, and other Building Energy Simulation (BES) tools.

Another recommendation has to do with dynamic façade's material. Currently in *DesignBuilder*, all materials have the same properties and as such have the same efficiency when used as a dynamic façade material. The inability of the software to consider the properties of dynamic façade material such as thermal properties (absorptivity, emissivity, and conductivity), durability, maintenance, cost, and other relevant properties in its calculations is a limitation that is affecting the efficiency of the dynamic façade. The properties of the dynamic façade material should be integrated in the modeling and simulation engine by the Building Energy Simulation (BES) tools.

The user should also be able to decide the number of materials (components) and the order of their arrangement from inside to outside of the dynamic façade. This is because in reality, the dynamic façade is a composition of different materials specifically selected and arranged to satisfy the conditions of its location as seen in the case of user-controlled dynamic façade of Kiefer technic showroom. The dynamic façade utilized in that instance consists of several layers including aluminum posts and Exterior Insulation and Finish System (EIFS)-façade transoms encased in white plaster. Therefore, the user should be able to select and modify the number of layers and their order of arrangement as it is in the case of construction components.

The efficiency of dynamic facade is directly linked to its configuration (settings). The configuration must satisfy both seasonal and orientation solar radiation demands of its location. It should be noted here that, the current configuration utilized in this research is location dependent. Meaning, it is only suitable for the current climatic conditions of Riyadh, Saudi Arabia. Therefore, if dynamic façade is to be employed anywhere, the configuration must satisfy these 2 conditions of its location.

Currently, the panels of dynamic facades are designed for universal purpose to be used for any given location. The efficiency of dynamic facades can be increased if dynamic façade panels are designed specifically based on the solar azimuth of a given location. This will block and reflect more solar radiation that come its way and hence improve its efficiency. Also, dynamic façade materials should be perforated to allow daylight instead of being opaque when fully closed. This will increase daylight utilization and reduce lighting energy consumption within the building and hence improve its efficiency. Future research in this area should examine material impact, operation cost, and the cost benefit analysis of dynamic facades on a life cycle perspective.

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APPENDIX A

Lighting Energy Consumption W/m^2 (West)

Time	1st Technique	2nd Technique	T	Floor No.
0	0.825	0.825	85%	11
1	0.825	0.825	85%	11
2	0.825	0.825	85%	11
3	0.825	0.825	85%	11
4	0.825	0.825	85%	11
5	0.825	0.825	70%	10
6	0.495	0.495	70%	10
7	0	0	45%	9
8	0	0	45%	9
9	0	0	20%	8
10	0	0	0%	7
11	0	0	0%	7
12	0	0	0%	7
13	0	0	0%	7
14	0	0	20%	8
15	0	0	45%	9
16	0	0	45%	9
17	0	0	70%	10
18	0	0	70%	10
19	0.825	0.825	85%	11
20	0.825	0.825	85%	11
21	0.825	0.825	85%	11
22	0.825	0.825	85%	11
23	0.825	0.825	85%	11
Total	9.57	9.57		

APPENDIX B

Total Cooling Energy W/m^2 (West)

Time	1st Technique	2nd Technique	T	Floor No.
0	0	0	85%	11
1	0	0	85%	11
2	0	0	85%	11
3	0	0	85%	11
4	0	0	85%	11
5	0	0	70%	10
6	0	0	70%	10
7	60.16435	60.10383	45%	9
8	66.53452	66.48814	45%	9
9	94.47868	94.41725	20%	8
10	102.4568	102.4568	0%	7
11	106.6969	106.6969	0%	7
12	110.329	110.329	0%	7
13	101.2111	101.2111	0%	7
14	150.6053	150.5755	20%	8
15	184.3679	184.3557	45%	9
16	195.1631	195.2734	45%	9
17	176.7211	176.8967	70%	10
18	96.61503	96.82052	70%	10
19	0	0	85%	11
20	0	0	85%	11
21	0	0	85%	11
22	0	0	85%	11
23	0	0	85%	11
Total	1445.34378	1445.62484		

APPENDIX C

Solar Gains Exterior Windows W/m^2 (South)

Time	1st Technique	2nd Technique	T	Floor No.
0	0	0	85%	11
1	0	0	85%	11
2	0	0	85%	11
3	0	0	85%	11
4	0	0	85%	11
5	0	0	70%	10
6	4.35265	4.35265	70%	10
7	13.542	13.542	45%	9
8	18.77999	18.77999	45%	9
9	22.50867	22.50867	20%	8
10	23.56779	23.56779	0%	7
11	23.41873	23.41873	0%	7
12	23.23098	23.23098	0%	7
13	23.61126	23.61126	0%	7
14	23.54027	23.54027	20%	8
15	23.90565	23.90565	45%	9
16	20.2735	20.2735	45%	9
17	15.97552	15.97552	70%	10
18	7.608577	7.608577	70%	10
19	0.4761318	0.4761318	85%	11
20	0	0	85%	11
21	0	0	85%	11
22	0	0	85%	11
23	0	0	85%	11
Total	244.7917188	244.7917188		

APPENDIX D

Lighting Energy Consumption W/m^2 (South)

Time	1st Technique	2nd Technique	T	Floor No.
0	0.825	0.825	85%	11
1	0.825	0.825	85%	11
2	0.825	0.825	85%	11
3	0.825	0.825	85%	11
4	0.825	0.825	85%	11
5	0.825	0.825	70%	10
6	0.45375	0.45375	70%	10
7	0	0	45%	9
8	0	0	45%	9
9	0	0	20%	8
10	0	0	0%	7
11	0	0	0%	7
12	0	0	0%	7
13	0	0	0%	7
14	0	0	20%	8
15	0	0	45%	9
16	0	0	45%	9
17	0	0	70%	10
18	0.0825	0.0825	70%	10
19	0.825	0.825	85%	11
20	0.825	0.825	85%	11
21	0.825	0.825	85%	11
22	0.825	0.825	85%	11
23	0.825	0.825	85%	11
Total	9.61125	9.61125		

APPENDIX E

Total Cooling Energy W/m^2 (South)

Time	1st Technique	2nd Technique	T	Floor No.
0	0	0	85%	11
1	0	0	85%	11
2	0	0	85%	11
3	0	0	85%	11
4	0	0	85%	11
5	0	0	70%	10
6	0	0	70%	10
7	40.02376	40.41569	45%	9
8	53.20409	53.76039	45%	9
9	82.35835	82.86295	20%	8
10	91.75835	91.75835	0%	7
11	96.76327	96.76327	0%	7
12	100.4802	100.4802	0%	7
13	79.98998	79.98998	0%	7
14	99.25429	99.77282	20%	8
15	104.3518	104.9008	45%	9
16	104.3518	104.9008	45%	9
17	102.7378	103.3039	70%	10
18	60.68634	61.21301	70%	10
19	0	0	85%	11
20	0	0	85%	11
21	0	0	85%	11
22	0	0	85%	11
23	0	0	85%	11
Total	1015.96003	1020.12216		

APPENDIX F

Solar Gains Exterior Windows W/m^2 (East)

Time	1st Technique	2nd Technique	T	Floor No.
0	0	0	85%	11
1	0	0	85%	11
2	0	0	85%	11
3	0	0	85%	11
4	0	0	85%	11
5	0	0	70%	10
6	18.41716	18.41716	70%	10
7	82.35719	82.35719	45%	9
8	129.0611	129.0611	45%	9
9	128.3726	128.3726	20%	8
10	96.23637	96.23637	0%	7
11	50.14559	50.14559	0%	7
12	24.39714	24.39714	0%	7
13	23.41742	23.41742	0%	7
14	23.54027	23.54027	20%	8
15	23.90565	23.90565	45%	9
16	20.2735	20.2735	45%	9
17	15.97552	15.97552	70%	10
18	7.608577	7.608577	70%	10
19	0.4761318	0.4761318	85%	11
20	0	0	85%	11
21	0	0	85%	11
22	0	0	85%	11
23	0	0	85%	11
Total	644.1842188	644.1842188		

APPENDIX G

Lighting Energy Consumption W/m^2 (East)

Time	1st Technique	2nd Technique	T	Floor No.
0	0.825	0.825	85%	11
1	0.825	0.825	85%	11
2	0.825	0.825	85%	11
3	0.825	0.825	85%	11
4	0.825	0.825	85%	11
5	0.825	0.825	70%	10
6	0.350625	0.350625	70%	10
7	0	0	45%	9
8	0	0	45%	9
9	0	0	20%	8
10	0	0	0%	7
11	0	0	0%	7
12	0	0	0%	7
13	0	0	0%	7
14	0	0	20%	8
15	0	0	45%	9
16	0	0	45%	9
17	0	0	70%	10
18	0.0825	0.0825	70%	10
19	0.825	0.825	85%	11
20	0.825	0.825	85%	11
21	0.825	0.825	85%	11
22	0.825	0.825	85%	11
23	0.825	0.825	85%	11
Total	9.508125	9.508125		

APPENDIX H

Total Cooling Energy W/m^2 (East)

Time	1st Technique	2nd Technique	T	Floor No.
0	0	0	85%	11
1	0	0	85%	11
2	0	0	85%	11
3	0	0	85%	11
4	0	0	85%	11
5	0	0	70%	10
6	0	0	70%	10
7	99.72902	99.8218	45%	9
8	136.033	136.1145	45%	9
9	173.2944	173.4458	20%	8
10	168.6198	168.6198	0%	7
11	139.2744	139.2744	0%	7
12	123.3023	123.3023	0%	7
13	98.32768	98.32768	0%	7
14	116.5044	116.5651	20%	8
15	122.6418	122.6727	45%	9
16	119.509	119.5366	45%	9
17	115.5037	115.5037	70%	10
18	72.59324	72.59324	70%	10
19	0	0	85%	11
20	0	0	85%	11
21	0	0	85%	11
22	0	0	85%	11
23	0	0	85%	11
Total	1485.33274	1485.77762		

APPENDIX I

Solar Gains Exterior Windows W/m^2 (North)

Time	1st Technique	2nd Technique	T	Floor No.
0	0	0	85%	11
1	0	0	85%	11
2	0	0	85%	11
3	0	0	85%	11
4	0	0	85%	11
5	0	0	70%	10
6	8.280039	8.280039	70%	10
7	25.9781	25.9781	45%	9
8	28.56692	28.56692	45%	9
9	26.44248	26.44248	20%	8
10	24.35863	24.35863	0%	7
11	23.33089	23.33089	0%	7
12	22.86453	22.86453	0%	7
13	23.41742	23.41742	0%	7
14	23.98959	23.98959	20%	8
15	26.93964	26.93964	45%	9
16	28.40435	28.40435	45%	9
17	28.34587	28.34587	70%	10
18	15.9432	15.9432	70%	10
19	0.4761318	0.4761318	85%	11
20	0	0	85%	11
21	0	0	85%	11
22	0	0	85%	11
23	0	0	85%	11
Total	307.3377908	307.3377908		

APPENDIX J

Lighting Energy Consumption W/m^2 (North)

Time	1st Technique	2nd Technique	T	Floor No.
0	0.825	0.825	85%	11
1	0.825	0.825	85%	11
2	0.825	0.825	85%	11
3	0.825	0.825	85%	11
4	0.825	0.825	85%	11
5	0.825	0.825	70%	10
6	0.350625	0.350625	70%	10
7	0	0	45%	9
8	0	0	45%	9
9	0	0	20%	8
10	0	0	0%	7
11	0	0	0%	7
12	0	0	0%	7
13	0	0	0%	7
14	0	0	20%	8
15	0	0	45%	9
16	0	0	45%	9
17	0	0	70%	10
18	0	0	70%	10
19	0.825	0.825	85%	11
20	0.825	0.825	85%	11
21	0.825	0.825	85%	11
22	0.825	0.825	85%	11
23	0.825	0.825	85%	11
Total	9.425625	9.425625		

APPENDIX K

Total Cooling Energy W/m^2 (North)

Time	1st Technique	2nd Technique	T	Floor No.
0	0	0	85%	11
1	0	0	85%	11
2	0	0	85%	11
3	0	0	85%	11
4	0	0	85%	11
5	0	0	70%	10
6	0	0	70%	10
7	52.74059	53.13091	45%	9
8	64.78114	65.31085	45%	9
9	90.16228	90.65679	20%	8
10	95.99031	95.99031	0%	7
11	99.67864	99.67864	0%	7
12	103.5393	103.5393	0%	7
13	82.07075	82.07075	0%	7
14	102.1438	102.6158	20%	8
15	108.2555	108.7669	45%	9
16	108.2555	108.7669	45%	9
17	108.2555	108.7637	70%	10
18	73.26649	73.78072	70%	10
19	0	0	85%	11
20	0	0	85%	11
21	0	0	85%	11
22	0	0	85%	11
23	0	0	85%	11
Total	1089.1398	1093.07157		

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