Geometry optimization of building-integrated photovoltaic sunshade

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Abstract

Building-integrated photovoltaic (BIPV) systems are one of the growing applications of PV technology. These approaches allow PV panels to perform additional functions for the building, such as regulating interior lighting and incoming heat. In this work, we explore a design framework for optimizing the configuration of BIPV shading devices to optimize a combination of power generation, daylighting conditions within the building, and heating and cooling loads.

We develop a generalizable computational model and apply it to a case study for the Cornerstone Architecture Building in London, Ontario. We optimize the configuration of static and dynamic BIPV shading devices in both horizontal and vertical configurations. Then, we compare the overall performance of these systems with each other and passive shades as well as conventional windows with no shades.

Keywords

Building-integrated photovoltaics, BIPV, Solar cells, Multi-objective optimization, Shading device.
Summary for Lay Audience

The potential of solar energy is vast compared to the other sources of renewable energy. A photovoltaic (PV) system is designed to generate electricity from this clean, cheap and abundant source of energy by using photovoltaic materials. Photovoltaics consist of solar cells which absorb and convert sunlight into electricity.

Building-integrated photovoltaic (BIPV) systems are a promising application of PV that has attracted increasing attention in recent years and plays an important role in achieving the goal of buildings with zero net energy consumption (net-zero energy building). BIPV refers to the integration of photovoltaic modules with dual purposes of replacing building components and simultaneously generating electricity. Photovoltaic panels can be used as shading devices in both new and existing buildings. They generate electricity and simultaneously improve the thermal and lighting conditions of the interior. While previous studies have compared different configurations and objectives for BIPV shades, the full design of such shades, particularly considering lighting, thermal, and power objectives had not yet been explored.

A computational framework is developed to optimize the design of building-integrated photovoltaic sunshades. BIPV shading devices are modeled in both static and dynamic format in horizontal and vertical layouts.

Results for a case study office building in London, Ontario, show that in static systems, vertical shades on east-facing windows generate more electricity than horizontal shades, but are not able to reduce the glare from direct sunlight as successfully. Therefore, the specific configuration (horizontal or vertical layout) depends on the relative preference for daylighting.

It is also concluded that dynamic BIPV window shades (shade with time-varying angle) have higher overall performance than static BIPV shades, and as the frequency of changing the angle increases (changing the angle every hour instead of every season or twice a year) the difference in overall performance compared to static system increases as well.

Finally, the framework developed here is general and can be used for optimizations for arbitrary building specifications and locations.
Acknowledgments

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Chapter 1

1 Introduction

1.1 Overview

Energy is one of the main pillars of modern society. However, a significant part of the global need for energy is provided by fossil fuels. For instance, in 2014, 81% of global energy consumption was provided by fossil fuels [1]. Burning fossil fuels to provide energy releases carbon dioxide, nitrogen oxides, and other greenhouse gases into the atmosphere which results in serious environmental problems such as global warming, climate change, and air pollution [2].

Renewable energy due to its lack of harmful emissions, is one promising way to tackle this issue. Solar energy is one of the most widely utilized renewable energy since it is the most abundant, clean, and cheap source of energy among all renewable sources of energy [3]. Photovoltaics (PVs) allow direct conversion of the sun’s energy into electricity and are one of the fastest-growing segments of the renewable energy industry [4].

A PV cell is made of semi-conductor materials which are excited when they are exposed to solar energy. The semi-conductor materials captures the photons emitted from the sun. When these photons are absorbed by these materials, they create an electron-hole pair. Different PV materials have different energy band gaps which make the absorption capacity different. If the energy of the photons are equal to that energy band gap of PV cell materials, they create free electrons which their movement in the same direction under an internal electric field creates a current. This internal field is consisted of the combinations of materials with positive charges (p-type) and negative charges (n-type) [5, 6]. These solar cells create a solar module which can be used to generate electricity current as shown in Figure 1-1.
Several net-zero energy building (NZEB) goals have been set by California Public Utilities Commission (CPUC) within the state that all new residential and commercial construction must be net-zero energy building by 2020 and 2030, respectively. The EU countries are also required to achieve an NZEB annual energy balance for all new buildings by 2021 [7]. Building-integrated photovoltaics (BIPVs) are one of the influential strategies to realize net-zero energy and zero-carbon building [8].

BIPV systems are an intriguing application of PV technology to help buildings partially meet their power needs by generating electricity [9] and thereby reducing their environmental impacts [10]. BIPVs are photovoltaic materials used to replace conventional building components such as façades, window covers, skylights, and roof, and can be used in the construction of new buildings or retrofitted in the existing buildings [11]. As an example, research showed that BIPV systems produce more electricity than conventional PV rooftop systems [12]. In addition, replacing the conventional building components by photovoltaic materials reduces the cost of additional assembly components such as brackets, rails, etc [13].

Figure 1-1: A schematic of different components of typical PV cell from Ref. [5].
Generating electricity is not the only purpose of BIPV, as these devices can act as external shading devices of buildings as well [14]. This can produce added benefits of reducing the heating and cooling loads and improving the visual comfort of the interior space [12]. Figure 1-2 displays a schematic of single BIPV shade and multiple BIPV shades on a window.

![Figure 1-2: A schematic of two common configurations of BIPV shading devices.](image)

### 1.2 Objectives

The objective of this thesis is fully optimizing the design of BIPV window shade considering the power generation, thermal and lighting analysis for specific location of our case study. We approach this optimization from the stand point of radiative solar energy transfer.
We do not take into account the effect of convection and conduction in our optimization. Due to the complexity of these calculations, the effects of convection and conduction are not included in the optimization and they are outside the scope of this thesis.

1.3 Motivations

Although BIPV shades are able to reduce the solar heat gain through windows on hot days of the year and improve the visual comfort of the space, their potentially negative effect on the heating load in the winter and indoor daylight conditions cannot be neglected. Therefore, it is necessary to develop a design framework to optimize the configuration of the BIPV shading devices which takes into account the considerations regarding the reduction of the cooling loads in the summer, the increase of the heating loads in the winter, the reduction of the natural light and glare, the reduction of the view outside, and the effect of self-shading of PV panels on the performance of the system [15].

The project described herein involves the creation of a computational framework to optimize the design of building-integrated photovoltaic sunshades. Such shades would allow improved lighting conditions within the indoor environment while generating power through the photovoltaic panels. The design framework takes in design constraints such as the allowable size of the shades, the location and orientation of the building, and properties of the photovoltaics of interest, and provides the user with a design maximizing the overall performance of the system by improving daylighting conditions, thermal performance and changes in heating and cooling loads, as well as electricity production.

There are two general goals in this project. The first is to develop a computational framework for an optimal design of BIPV shades, and the second is utilizing this framework to assist in the development of a case study for one such system. The purposes of the computational model in the first goal are to:

- Improve daylighting
- Reduce glare
- Reduce heating and cooling loads
- Optimize energy production
The model will take in necessary design constraints and return the calculated parameters corresponding to the optimal design of the shade, provided appropriate weighting between the given objectives. This model will be general and able to be applied to any situation where an optimized photovoltaic shade is desired.

The second goal is the development of a case study for one such implementation of a shade at the Cornerstone Architecture building. This will both provide the company with a design of a product that they can utilize and benefit from, while also working as a validation of the accuracy of the framework.

1.4 Thesis organization

A mathematical model is developed in MATLAB to take inputs of the design constraints and objectives. The code then references databases of information containing material and performance properties of the solar cells being used, of the daily and yearly average insolation conditions (including average weather data), and runs through an optimization to determine the ideal design of the solar shades.

The code has the general structure to:

- Accept inputs of environmental conditions
  - Radiation intensity (direct and diffuse)
  - Ambient temperature
  - Wind speed
- Accept inputs of solar cell parameters
  - Efficiency
  - Absorption
- Accept inputs of design constraints
  - Size of array, maximum and minimum number of elements, angular restrictions
  - Building location and orientation
- Accept inputs of design objectives
  - Ideal light levels
- Trade-off between the value of power and lighting quality
- Maximum and minimum of comfortable indoor temperature

- Provide outputs of the optimal design of the solar shade including:
  - Number of shades
  - Angle of shades (static and time-varying)
  - Length of shades

We begin by collecting and integrating existing data on solar conditions for a given location (London, Ontario), both in terms of existing databases of actual measurements (which incorporate real weather conditions and solar insolation levels), as well as general models (for when measurement databases are not available).

We utilize a computational Monte Carlo optimization method to find the best combination of quantity, length, and angle of shades for each window. We use a Monte Carlo method due to its simplicity and low computational cost. We define different objectives to use for the optimization and they are used as criteria for optimization either alone, or in combinations together.

The model is evaluated for the conditions at the Cornerstone Architecture office with solar cell properties of common solar cells available in the market. Shades are modeled in horizontal and vertical layouts, and the performance of the system is then investigated in the static and dynamic models, in comparison with each other and the system with no shades as the baseline.

### 1.5 Chapter outline

The thesis is written in monograph format with six chapters which are listed below.

Chapter 2 summarizes the previous works about BIPV shading devices and indicates the gap in those studies which needs to be filled.

In Chapter 3, we discuss the methodology of the framework. Different solar angles are defined to calculate the radiation incidence on the panels and windows. Then, the
optimization method and the way it uses different value functions to select the optimum
design parameters are explained.

In Chapter 4, the static model is investigated. First, a simple case is defined to compare
different layouts (horizontal and vertical). Then, the Cornerstone Architecture office case
study is introduced and different configurations are discussed. Also, the results are
compared with different cases such as passive shades and case with no shades on the
windows. At the end, a validation study of the lighting performance of the system is
discussed.

In Chapter 5, the dynamic version of the model is explored. We define three types of
dynamic models and compare them with each other and with the static model.

In Chapter 6, the overall results and conclusion are stated, and limitations and strength of
the model as well as future recommendations are discussed.
Chapter 2

2 Literature review

Due to the fast pace growth of PV technology compared to the other types of renewable energy technologies, this area is one of the research hotspots that attracts a lot of attention in the last years. As a part of this expansion, building-integrated photovoltaic (BIPV) systems are one specific application of this technology that has received growing interest. This technology refers to the integration of photovoltaic modules into the building envelopes [3] with two main purposes of replacing conventional building components and saving energy by converting incident sunlight into electricity [16]. This chapter presents a review of current BIPV shading optimization research, as well as opportunities to expand the field.

2.1 Background

One of the main solutions to control heat gain into the buildings and provide a visually comfortable space is using shading devices. Although PV was first used in the late 1970s, it was introduced as a building-integrated component for the first time in 1991 [17]. In 1998, Yoo and Lee [18] came up with the idea of using integrated photovoltaics as a shading device for the first time. PV as shading devices can be applied in both new and existing buildings since they are attached as an external building layer. The two important advantages of this technology are saving energy by generating electricity directly from incident sunlight and working as external blinds to protect the building from overheating and providing acceptable indoor conditions [3].

2.2 Power generation

In this section, we review the past works that have optimized a few design parameters, with one objective and that often combined a few parameters together (heat and electricity production). In these studies, the analysis of the thermal performance of the system was only the investigation of the influence of solar shades on the reduction of cooling loads, but the detrimental effects of shades on heating load in the cold days of the year were not considered. One of the most important parameters determining the performance of a
photovoltaic shading device is the angle of inclination, which depends strongly on the building’s geographical location, the orientation of the building, and the type of the shading device [19].

The energy performance of the shading-type BIPV claddings is investigated by Sun et al. [20]. They defined electricity-saving produced by the shading-type BIPV claddings as an objective function which includes electricity generation by PV modules and electricity consumption reduction caused by the cooling load reduction to evaluate the optimum position of the claddings. They analyzed the impact of the tilt angles and surface azimuth angles of the PV modules, the window to wall ratio (the ratio of the window height to the exterior wall height) of the building, and the overhang length on the electricity savings. It should be mentioned that their system consists of only one shade on each window.

They investigated the optimum design of the shading-type BIPV claddings for buildings with different orientations and window to wall ratios in Hong Kong. Despite the fact that they investigated different orientations and sizes of the windows, their research was limited to the horizontal configuration of BIPV claddings. They found out that with the same window to wall ratio and overhang length, shades with a higher tilt angle generate more electricity. The main focus of their research was on the electricity generation and heat flux of the sunlight and they did not consider the effect of the BIPV claddings on the quality of the lighting of the office, while one of the most important applications of claddings is controlling the daylighting of the space.

Sun et al. [21] in another study, discussed the impact of building orientations, inclinations, and wall utilization fractions on the energy performance of the shading-type BIPV claddings in terms of the annual power output of PV modules and cooling load reduction of windows and concrete walls. They used the “radiant time series (RTS)” method which is derived from the heat balance (HB) method to calculate the cooling load of windows and concrete walls by quantifying each component’s contribution to the total cooling load. They also analyzed each contribution of the total electricity saving of shading-type BIPV claddings such as electricity generated by PV panels, window, and concrete wall cooling load reduction. The wall utilization factor was defined as the ratio of the height of the
concrete walls installed with PV modules to the total height of concrete wall and it was concluded that the shading-type BIPV claddings are more cost-effective when installed with smaller wall utilization fractions rather than larger ones.

Their results showed that shading-type BIPV claddings have a significant effect on cooling load reduction of windows and concrete walls. It was concluded that south and southwest are the two best choices for PV module installation for the weather in Hong Kong and the optimum tilt angles for different designs vary from 30° to 50° from the horizon. Although their optimization of the BIPV shading system included the power production and thermal performance of the system, it did not take into account the effect of daylighting conditions on the optimization results.

Different tilt angles and orientations of PV shading devices were compared and evaluated by Tongtuam et al. [22]. They demonstrated that the tilt angle of 60° to the vertical on south, southeast or southwest direction would result in maximum energy production. They evaluated the effect of diffuse radiation reflection from the exterior wall to evaluate the annual energy yield per square meter of a single PV shading device with different slopes and directions. While strongly influencing the system’s efficiency, the inclination angle cannot be used as the only criterion to decide the optimum design of the system.

In another study, Yoo modeled and optimized BIPV as shading devices through an “ecological convergence” of a passive solar architecture and photovoltaic system. They identified the energy usage pattern and yearly energy consumption of 17 buildings in Seoul, South Korea, for a refurbishment with renewable energy system and chose one of those buildings for simulation to remodel the BIPV shading system with TRNSYS 17 as their case study (Figure 2-1) [12]. They also used the simulation program “SOLCEL 19” to evaluate the thermal comfort characteristic, the solar irradiance on PV modules, and the amount of cooling load reduction caused by shades. Their model was one of the only studies that considered the effect of surrounding obstacles on the power generation.

Their calculation showed that the total amount of power generation of the PV shades with the tilt angle of 75° to the vertical axes is 4% more than the conventional PV rooftop system at the same angle and it covers 32% of total energy consumption of the building for a year.
Their system also reduced the cooling load by 32-34% for their case study which experiences high cooling load during the summer in that region.

![Simulation model of PV shading system](image)

**Figure 2-1: Simulation model of PV shading system in Ref. [12].**

Budhiyanto et al. [23] also investigated the economic performance of these systems by simulating six BIPV models with different designs of BIPV devices for east and west walls of a ten-story office building which was modeled within EnergyPlus simulation software. Panels with a constant length and width were installed at the angle of 30° to the horizon, but the number of the shades and the distance between them were different in each model.

They concluded that a properly designed BIPV shading system would be economically beneficial. In their case, installing fewer BIPV shading devices with longer distances between them were more effective than installing more shades with less distance, since the amount of energy-saving and energy produced was not equal to the number of BIPV shading devices installed.

### 2.3 Multi-objective optimizations

In the following section, the papers that optimized a few design parameters, with multiple objectives including lighting, heat, and power production are discussed.
Taveres et al. [24] presented a methodology to optimize the design of a fixed PV integrated shading devices (PVSDs) on the southern face of an office building in Oslo, Norway, based on a multi-objective optimization “(MOO)”. Their optimization included thermal, electric, and lighting simulation. Their inputs for the optimization were the number of shades, their tilt angle, and position along the vertical axis. They defined three objectives for their optimization which were minimizing the total annual net electricity use (sum of electrical energy use for heating, cooling and artificial lighting discounted for the energy converted by the PV panels), maximizing the amount of energy converted into electricity by PV cells and maximizing the daylight level in the zone measured as the continuous daylight autonomy (cDA [%]). The continues daylight autonomy (cDA) calculates the number of working hours during a year in which a specific surface in a room receives an amount of light over a given threshold [25]. Although the influence of electricity generation by PV cells was accounted for in the calculation of total annual electricity use, they chose it as their second objective, because they wanted to maximize the return of their investment by using PV materials.

They modeled their building and shades in the Grasshopper software and the energy calculations were done by HoneyBee. Their optimization process was done by the genetic multi-objective optimization and each complete run of their optimization took 10 days. To reduce the computational time, they used simplified and conservative daylighting calculation and “low quality” radiance setting in the Grasshopper. The solar cell reflection was also considered constant (10%) which in real condition is dependent on the angle of incident [26]. Their objectives had been weighted with the same value but in the reality, their importance must be chosen by the user. Also, the model is only capable of optimizing all objectives at the same time and it cannot optimize the configuration based on the objectives separately, and the optimization was limited to the south-facing windows. Furthermore, the optimization model did not have the ability to optimize the design parameters (the number of the shades, their size, and angle) all together and it can only provide the optimum angle.
On the other hand, one of the unique aspects of their research is that they assessed the performance of their optimization results from aesthetic and architectural point of view and they investigated the possibility of manufacturing as a real shading system.

In another study [27], the same authors appraised the relation between annual solar energy conversion potential and annual visual comfort levels in the room. The purpose of their methodology was determining the effect of the geometry of the system (number and angle of the shades) on the electricity conversion and daylight availability of the room by comparing different configurations related to the number of the shades and their tilt angle, but the size of the shades and their thickness were kept constant. The number of the shades were limited from 10 to 22, equally spaced, where have a homogenous tilt angle of 0°, 15°, 30°, and 45° from the horizon.

While the annual radiation analysis of their research took into account both direct and diffuse radiation, the lighting analysis did not distinguish these two. They found that the two best configurations were 16 shades at the tilt angle of 15° or 22 shades at 0°. Both of these configurations performed very well in power generation while 22 shades bring slightly improved cDA value.

Zhang et al. [14] developed a numerical simulation in EnergyPlus to investigate the effect of different tilt angles and orientations on the energy-saving potential of BIPV shading devices in Hong Kong. They also compared the energy-saving potential of solar PV shadings with that of interior blinds. They calculated the optimum angle (angles between 0° to 90° in steps of 10°) and orientations (east, south, west, southeast, and southwest) of PV shades in three different scenarios to maximize the annual electricity generation, minimize the annual cooling loads and minimize the annual increased lighting electricity, individually. They also optimized the configurations of the shades to achieve the highest overall electricity benefits in a combination of power, thermal and daylighting performance. However, the number and area of the shades were fixed during the optimization with only the angle of shades being varied (Figure 2-2).

Their results indicated that to maximize the power production of the solar panels, shades should be installed on the south façade with the tilt angle of 30° to the vertical. However,
if the objective is maximizing the overall electricity benefits by considering the electricity savings from the air-conditioning system and the increased electricity consumption for artificial lighting, the optimum tilt angle of shades on the south façade would be 20°.

Despite the fact that they analyzed the lighting performance of the system by calculating the amount of increased electricity consumption of artificial lighting, they did not take into account the user’s preference of natural daylighting over artificial lighting in their calculations.

![Figure 2-2: A generic model simulated in EnergyPlus in Ref. [14].](image)

Bahr [15] studied the application of PV blinds on a vertical glass curtain wall. He set nine different installation options of PV blind system with two different PV panel types (crystalline silicon and amorphous silicon thin films) and compared them based on a cost-benefit approach. The methodology included the thermal comfort, visual comfort, and energy-savings requirements and quantified the profit-rate of each design solution over a one year period. To calculate the benefit of each design solution in terms of energy production and energy savings, he took into account the capital cost (initial cost) and running costs (maintenance costs) of PV blinds. He assessed the design options through computer simulations by modeling a two-story building in Abu-Dhabi with Ecotest.
The results revealed that crystalline panels have a higher profit-rate despite their higher cost and intolerance to partial shading effect. Regardless of the multiple criteria in the analysis, the glare was not taken into account in the lighting analysis. Also, the effect of user’s preference between natural and artificial lighting on the results was neglected too.

### 2.4 Different configurations

Other papers compared different types of shading devices and investigated their performance according to their geometrics. Asfour [28] compared the performance of the horizontal and vertical installation configurations of the shading devices on the west, east, and south façades in a hot climate zone in Saudi Arabia. He investigated the amount of insolation received by PV panels and the amount of shading secured for windows for eight different configurations which included horizontal and vertical shades with the same PV area with the inclination angles of 0°, 30°, 45°, and 60° in both summer and winter. However, the research did not consider the effects of these configurations on the natural light and daylighting level of the space. In this study, the number and length of the shades were not optimized and it was assumed that each floor has one entire shade with the length of 1m (Figure 2-3).

![Figure 2-3: The horizontal (H-SD) and vertical (V-SD) modeling cases in Ref. [28].](image-url)
They simulated the performance of the shading devices with Design Builder 5.4 software. To validate the results, he compared them with outputs of other simulation software including IES VE 2018 and Ecotest Analysis 2011. He took an average for incident solar radiation over the shading devices as a daily total insulation average for both summer and winter which is not as accurate as the hourly average.

The results demonstrated that horizontal shading devices installed on the windows on the eastern, southern, and western façades have better performance in general compared to vertical shades. However, he did not take into account the effect of the ambient temperature on the solar cell efficiency and power production especially in a location like Saudi Arabia where temperature variation is highly intense. This study could be improved by also analyzing the dynamic shading system in which the shade inclination is not constant and it can change to be at an optimized position and perform efficiently in both summer and winter.

Mandalaki et al. [29] additionally investigated the performance of different PV shading devices with varying configurations and dimensions. They used computer simulation software (EnergyPlus and Autodesk Ecotest) to model and compare thirteen types of fixed shading devices in two different latitude points. This research demonstrated that the surrounding-shading type (Figure 2-4) is the most efficient configuration of shading devices. It is also the most energy-efficient system, assuming the electricity produced from the PV can be used for heating and cooling the space. However, their result was limited to only southern window orientation.
Figure 2-4: Thirteen types of shading devices investigated in Ref. [29].

Five different building façade layouts including horizontal and vertical louvers (Figure 2-5) were modeled in Rhinoceros using Grasshopper and optimized for maximum annual solar irradiation in Freitas research [30]. The case study was a simple parallelepiped room in Lisbon, Portugal where façades on the east, south, and west sides were studied. While their model contained windows in different directions, it did not take into account the surrounding obstacles.

Each scenario was optimized by a single-objective optimization process. They used an evolutionary solver to maximize the overall annual solar radiation incident on the façade features. In their optimization, louver’ lengths were kept constant, while the tilt and
orientation of the louvers were changed in every iteration. In this study, the power production of the panels and lighting condition of the room were not investigated and only solar radiation incidence on the façade was considered as an objective in the research.

Their results indicated that horizontal louvers achieve higher energy yields per m² by allowing a more than 25% increase in incident solar radiation than purely vertical configurations.

**Figure 2-5: Five different façade layouts studied in Ref. [30].**

Freewan [31] studied the effects of three types of fixed shading devices (vertical fins, diagonal fins, and egg-crate, Figure 2-6) on visual comfort and thermal performance of the south-west windows of an office building in Jordan. Although shading devices used in this study were not BIPV and power generation was not considered, controlling solar gain, improving daylighting, and reducing glare were the main objectives of this research.

**Figure 2-6: Shading devices installed in the tested offices in Ref. [31].**
His research consists of both real-time experiments and computer simulations (IES/Suncast and Radiance). The results demonstrated that all types of shading devices improved the thermal and visual comfort in the office compared to the base-case (windows with no-shades), but diagonal fins and egg-crate shading devices performed better than vertical fins.

## 2.5 Dynamic systems

In this section, we review papers that studied dynamic shading devices which their angle of the shades is not constant and changes in time. Nielsen et al. [32] investigated the potential of a dynamic solar shading system taking into account the thermal and lighting performance of the system for a case study in Denmark. They used iDbuild to simulate an office room with a window with three different types of façades; dynamic shades, static shades, and no-shades, in four different directions. The evaluation criteria of their comparison were total energy demand of the model, energy demand for heating, energy demand for cooling, and energy demand for artificial lighting. The changes in heating and cooling that they considered in their study were changes in thermal transport through the walls and windows and it did not include the heating and cooling load from sunlight itself. Although it was a multi-criteria simulation, they did not consider the possibility of power generation of solar shades in their study.

The results suggested that dynamic solar shades have the best performance compared to static shades and no-shades, but the difference in total energy demand between dynamic and static shades is negligible. However, in terms of daylight factors, dynamic solar shading improves the performance much more than fixed shades. While showing great performance in energy savings and visual comfort, economic aspects of dynamic shades (investment and maintenance) and feasibility of the system were not investigated.

Jayathissa et al. [33] investigated the energy performance of a building in Zurich, Switzerland by developing a dynamic photovoltaic system for adaptive shading to control solar heat gains, natural lighting, and power generation all at the same time. They also compared the performance of this system with a static shading system and a façade with no shading.
They modeled the shades in the Grasshopper environment to simulate the solar radiation on the panels. The self-shading of PV modules was included since the gap between modules was held constant at 100 mm (Figure 2-7). The area of the shades was also constant and the only design parameter being optimized was the orientation of the panels. Due to the computational expense of their model, the angle of the panels changed in 15° steps in both axes.

![Adaptive solar façade (ASF) of the case study in Ref. [33].](image)

Their goal was to choose the configuration among all possible simulated dynamic configurations for each hourly time step to minimize the net building energy demand, i.e. energy demand for heating, cooling, and lighting minus the BIPV electricity generation.

They also assumed a linear relationship between PV cell operating temperature and incident solar irradiance, but they did not take into account the effect of the wind on the PV cell operating temperature and efficiency. Their lighting model was based on the average illuminance of the room, but the visual comfort such as glare was not considered in their method. Also, there was no consideration of view through the window.

Their results demonstrated that an adaptive (dynamic) system would have 20-80% more net electricity savings compared to a static system depending on the efficiency of heating and cooling systems and the location of the building. For buildings in a warmer climate
such as Miami, a static system consisted of semi-transparent BIPV glasses, or optimally tilted louvers would be a preferred solution. They determined that during the year, the power generation by PV compensates for 61% of the annual energy demand, and it can reach up to 95% when average COPs increase to 6. The framework developed is able to be applied to different configurations, building systems, and climates to evaluate the energy performance of the PV systems, but it analyses the lighting condition of the space only in terms of energy savings and does not consider the user preference of natural lighting over artificial lighting. Moreover, it is not capable of optimizing all design parameters simultaneously. They consider a square array of panels with fixed size and distance between them and only the angle of the panels in two degrees of motion was optimized.

Elzeyadi [34] presented a framework to compare the performance of different dynamic shading typologies and evaluate their impacts on building energy savings, daylighting distribution, glare control, and solar insulation management for a typical office space in ASHRAE climate zone 4C. He categorized dynamic shades on six different typologies based on their ability to be adjusted to control and manage lighting, solar insulation, and thermal radiation on the building façades. The dynamic typologies were: automated exterior blinds, dynamic egg-crates, optical element panels, thermal change planes, stretched fabrics/weaved panels, and automated movable screens (deep planar screens, 3-D paramedic screens, and 3-D geometric screens, Figure 2-8).

Figure 2-8: Dynamic shade typologies studied in Ref. [34].
He concluded that out of those six systems, the dynamic screens, automated egg-crates/blinds, and thermal elements (e.g. electrochromic glazing) provide the most positive and consistent performance across most climates. Also, the most effective typology in controlling the glare is 3-D parametric screens as well as thermal elements and egg-crates.

However, the different dynamic shades were only tested on the south-facing façade and comparing the actual performance of the actual prototype of the dynamic shades was limited to only fully open and closed conditions.

### 2.6 Summary and perspective

In past studies, the energy performance of BIPV shading devices was investigated. The research analyzed the impact of different tilt angles, orientations, and configurations on the performance of the system. In recent years, multi-objective optimization has been applied in terms of power generation, thermal performance, and visual comfort. In other studies, the potential of dynamic BIPV shades is discussed to improve the performance of the system by increasing the control of solar heat gain, natural lighting, and power generation.

There is currently a knowledge gap in optimizing all design parameters of the BIPV shading system concurrently. In all previous studies (to the best of our knowledge), at least one design parameter was held constant while others were optimized. We are not aware of any studies that have optimized the number, length, and angle of PV solar shades all together. This is likely due to the fact that previous works largely utilized commercial lighting analysis software, as opposed to simplifying the systems to their basic geometry. The time requirements of using such software have previously made the computational cost of full optimization of the system prohibitive.

Additionally, the main focus of past works is largely on electricity production of the system, while the overall performance of the system consists of power production, thermal and visual performance. Studies that considered the thermal performance in their optimization only investigated the effect of shades on the cooling load reduction and the detrimental effects on the heating load in the winter were neglected. Also, in the systems that considered lighting performance in their optimization, the analysis of the daylighting
was purely in terms of energy-saving and the user preference of natural light over artificial light was not considered.

Previous works have also not considered the influence of diffuse and direct light separately in terms of interior lighting, and thus the negative influence of glare could not be fully accounted for. Models generally did not have the ability to analyze and compare different configurations such as horizontal and vertical shades in different directions. Most of these studies were limited to only one direction (usually south) as well.

Moreover, they did not consider the influence of hourly variation of radiation intensity on the solar cell efficiency as well as ambient temperature and wind speed. The majority of the past studies also did not take into account the effect of surrounding obstacles on the performance of the system and optimization results. We work to address all of these outstanding issues in the present thesis.
Chapter 3

3 Methodology

Our model takes in design constraints such as weather and radiation data of a specific location, building properties and orientation, solar cell properties, and other environmental effects such as surrounding obstacles, and provide the optimum design parameters of the BIPV shading system including angle, size, and number of the shades on each window with a multi-objective optimization which takes into account the power generation of PV panels, the thermal condition, visual comfort of the interior environment, and user preference in trade-offs between each of these objectives.

In this chapter, we discuss solar radiation, solar angles, panel properties, incident irradiance, and reflection losses. Then, the design parameters, the optimization objectives, and the optimization method are described. Figure 3-1 displays a schematic of the methodology of the framework studied in this thesis.

Figure 3-1: A schematic of the methodology of the framework.

3.1 Solar radiation data

For calculating the amount of energy produced by solar panels, we need to know how much energy is received from the sun. Radiation data is taken from the NASA website [35] for the city of London, Ontario (42.9849° N, 81.2453° W). Figure 3-1 shows the amount of
normal and diffuse radiation for this location. As shown in the figure, normal and diffuse radiation are at their highest value in the summer. Also, we can see that normal radiation is always higher than diffuse radiation.

Since the available data are only monthly averages, the simplest way to get the hourly radiation intensity is interpolating the monthly averages to daily values, and dividing the average daily values by 24 hours. However, the radiation intensity varies during different hours of the day, so the generated data would not be accurate. For addressing this issue, we compute an expected hourly radiation profile, and then scale the calculated hourly radiation profile, so that it integrates to the historical value. For this step, we need to define the air-mass concept which is explained in Section 3.3. But first, we need to introduce the definitions of solar angles.

![Figure 3-2: Historical monthly averages of normal and diffuse radiation for London during a year from Ref. [35].](image)

### 3.2 Solar angles

The sun’s total energy output is $3.8 \times 10^{20} \text{ MW}$ which radiates in all directions. Earth receives only a small fraction of the total energy, equal to $1.7 \times 10^{14} \text{ kW}$. Although Earth’s portion of the energy is small-scale, it is estimated that the amount of energy
received by Earth in 84 minutes can provide the world energy demand for one year (about 900 EJ, 1 exajoule = 10\(^{18}\) joules) [36].

To properly calculate the solar radiation falling on a specific location on Earth for using in the estimation of solar heat gain and photovoltaic energy production, we need the knowledge of the sun’s path through the sky. The first motion of the sun that comes to mind is its daily movement in an arc across the sky, reaching its highest point at midday.

For most solar energy applications, it is necessary to have an accurate prediction of the sun’s location in the sky at any time of the day and year. The main reason for the importance of the sun’s location in the sky is that reflections and self-shading strongly depend on the angle of incoming direct light to the surface of the array. Therefore, knowing the fact that direct light is more needed than diffuse light to generate electricity, predicting the sun’s path comes with great importance. The sun’s movement is limited to two degrees of freedom on the celestial sphere; therefore, its position with respect to an observer on Earth can be fully described by two astronomical angles, the solar zenith angle (\(\varphi\)) and solar azimuth angle (\(z\)) [36]. In the following section, each of these angles is described with its associated formulation. But, before talking about the equations of solar altitude and azimuth angles, it is essential to define another two solar angles; solar declination angle (\(\delta\)) and hour angle (\(h\)), since they are required in all solar angles formulation.

### 3.2.1 Declination angle

The axis of rotation of Earth is not parallel to the sun’s axis and is tilted by 23.45° and the declination angle (\(\delta\)) varies between plus or minus this amount. Only at the spring and fall, equinoxes declination angle is equal to 0° [36]. The rotation of Earth around the sun is displayed in Figure 3-2.
Figure 3-3: Annual motion of Earth around the sun and variation of declination angle ($\delta$) from Ref. [36].

The declination angle ($\delta$) can be calculated by the approximate equation of Cooper [37].

$$\delta = 23.45 \sin\left(360 \frac{284 + N}{365}\right)$$

where, $N$ is the number of days in a year.

Figure 3-3 illustrates the variation of the declination angle during a year.

Figure 3-4: Variation of declination angle ($\delta$) during a year.
3.2.2 Hour angle

The local standard time we use is not directly connected to the sun’s position due to factors such as the discrete size of the time zones and the eccentricity of Earth. To get an accurate calculation of the sun’s position with respect to local time, we need to correct for these factors. The hour angle \((h)\) of a point on Earth’s surface is defined as the angular displacement of the sun east or west of the meridian of that point due to the rotation of Earth on its axis at 15° per hour (Figure 3-4). The hour angle is zero at local solar noon, positive at the afternoon hours and negative at the morning hours. The hour angle in degree can be obtained from Equation 3.2 [36].

\[
h = (AST - 12) \times 15
\]

\[\text{AST is apparent solar time which can be calculated by [36]:}\]

\[
AST = LST + ET + 4(SL - LL) - DS
\]

where,

\[LST = \text{local standard time}\]

\[ET = \text{equation of time}\]

\[SL = \text{standard longitude}\]

\[LL = \text{local longitude}\]

\[DS = \text{daylight saving (it is either 0 or 60 min)}\]

If the location is east of Greenwich, England, the sign of the Equation 3.3 is minus (-), and if it is west, the sign is plus (+). \(DS\) depends on whether daylight saving time is in operation (usually from the end of March to the end of October) and usually is ignored.

\(ET\) (equation of time) can be calculated by Equation 3.4 [36]:

\[
ET = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B)
\]
Figure 3-5: The schematic depicting the hour angle \((h)\) and solar declination \((\delta)\) with respect to the orientation of Earth from Ref. [36].

3.2.3 Zenith angle

Zenith angle \((\varphi)\) is the angle between vertical and the sun’s ray, as shown in Figure 3-5. The mathematical expression for the zenith angle is [36]:

\[
\cos(\varphi) = \sin(L) \sin(\delta) + \cos(L) \cos(\delta) \cos(h)
\]  \hspace{1cm} 3.6

where, \(L\) is local latitude.

3.2.4 Azimuth angle

Azimuth angle \((z)\) is the angular displacement from the projection of the sun’s beam radiation to the south for northern hemisphere or north in southern hemisphere. Displacements at east of south are negative and west of south are positive. The mathematical expression for the azimuth angle is [36]:

\[
\sin(z) = \frac{\cos(\delta) \sin(h)}{\cos(\alpha)}
\]  \hspace{1cm} 3.7
This equation assumes that: \( \cos(h) > \frac{\tan(\delta)}{\tan(L)} \). If this condition is not satisfied, the azimuth angle for the morning hours is \(-\pi + |z|\) and for the afternoon hours is \(\pi - z\).

Figure 3-6: Definition of zenith angle (\(\phi\)) and azimuth angle (\(z\)) with respect to a given location on Earth from Ref. [36].

Figure 3-6 displays the variation of zenith and azimuth angles for London during a year. The shaded part of the plot represents the time that the sun is below the horizon (night time).

Figure 3-7: Variation of zenith and azimuth angles for London during a year.
3.3 Air-mass

Air-mass is the length of the path which light takes through the atmosphere normalized to the path when the sun is directly overhead. As light passes through the atmosphere, its power is reduced because of the absorption by air and dust and this reduction can be quantified by the air-mass. The air-mass is defined as [38]:

\[ AM = \frac{1}{\cos \varphi} \]  

(3.8)

where, \( AM \) is the air-mass and \( \varphi \) is the angle between the sun’s ray and the vertical (zenith angle), as shown in Figure 3-7.

Figure 3-8: The air-mass represents the proportion of the atmosphere that light must pass through before striking the earth relative to its overhead path length.

In the next section, we talk about how the air-mass concept is used to estimate hourly radiation intensity.

3.3.1 Hourly radiation intensity

Meinel [39] came up with an empirical relation using air-mass to calculate the intensity of the direct component of the sunlight.

\[ I_D = 1.353 \times 0.7^{AM^{0.678}} \]  

3.9
where, $I_D$ is the radiation intensity on a plane normal to the sun’s ray in units of kW/m$^2$ and $AM$ is the air-mass [38].

To calculate the hourly data, the computed profile from Equation 3.9 is rescaled, so that it integrates to the same values as the historical daily averages from Ref. [35]. Figure 3-8 shows the hourly normal and diffuse radiation for a year for London.

![Graph showing hourly normal and diffuse radiation for a year for London.](image)

**Figure 3-9:** Hourly normal and diffuse radiation during a year for London. Inset 1 displays the normal and diffuse radiation for a two-day period.

### 3.4 Incident irradiance

One of the critical steps of evaluating the performance of a PV system is the calculation of the incident irradiance on the plane of the array (POA) as a function of time. The POA irradiance is dependent upon several factors [40]:

- Sun position
- Array orientation (fixed or tracking)
- Irradiance components (direct and diffuse)
- Shading (near and far obstructions)
Total solar irradiance on a plane of the array can be divided into two components: beam component and diffuse component. Mathematically, the irradiance ($I_{POA}$) is [41]:

$$I_{POA} = I_b + I_d$$  \hspace{1cm} (3.10)

where, $I_b$ is the POA beam component and $I_d$ is the POA sky-diffuse component.

There are many models to estimate POA irradiance from standard components. We use one of the simple models for simplicity which is explained in the following section.

### 3.4.1 Beam radiation

The POA beam component of irradiance ($I_b$, also referred to as direct radiation) is calculated by adjusting the direct normal irradiance ($DNI$) by the angle of incidence ($AOI$) with the following equation [40]:

$$I_b = DNI \times \cos(AOI) \times \text{losses}$$  \hspace{1cm} (3.11)

$AOI$ and $\text{losses}$ will be discussed below.

### 3.4.2 Diffuse radiation

There are different models to estimate diffuse radiation. The isotropic sky-diffuse is the simplest of the POA sky-diffuse models. This model assumes that the diffuse radiation from the sky dome is uniform across the sky. The POA sky-diffuse irradiance ($I_d$) is calculated as a fraction of the measured diffuse horizontal irradiance ($DHI$) as [41],[42]:

$$I_d = DHI \times \frac{1 + \cos(\theta_T)}{2} \times \text{losses}$$  \hspace{1cm} (3.12)

where, $\theta_T$ is the tilt angle of the array.

### 3.4.3 Angle of incidence

Angle of incidence ($AOI$) is the angle between the sun’s ray and the direction normal to the exposed surface and can be determined with Equation 3.13 [43]:
\[
\cos(AOI) = \cos(\phi) \cos(\theta_T) + \sin(\phi) \sin(\theta_T) \cos(z - z_{array})
\]

where, \(\theta_T\) and \(z_{array}\) are the tilt and azimuth angles of the array, respectively.

The tilt angle of the array (\(\theta_T\)) is the angle of the array from horizontal and azimuth angle of the array (\(z_{array}\)) is the deviation of the projection of surface normal on a horizontal plane from the local meridian. So, if the array is facing south, the surface azimuth is zero, east is negative and west is positive; \((-180^\circ < z_{array} < 180^\circ)\) [43].

### 3.4.4 Reflection losses

There are different factors that can reduce irradiance incidence on the array such as soiling and reflection losses [40]. Various models have been developed to estimate these reductions. The model that we use to calculate the incident angle reflection losses is the Physical IAM Model.

As mentioned before, the angle of incidence (\(AOI\)) is the angle between the direct component of the solar radiation and normal to the panel surface. The angle of incidence is directly involved in the calculation of the incident radiation on the surface of the PV devices. Additionally, the angle of incidence influences the amount of solar radiation absorbed by the solar cells. At \(0^\circ\) (rays normal to the surface) the \(AOI\) is maximized (=1), and as the angle increases, the amount of solar radiation reflected from the panel increases too, with angles greater than \(65^\circ\) causing significant reduction [26].

The influence of the angle of incidence is incorporated by defining the “angle of incidence modifier”, \(IAM (\theta)\), which is the ratio of the radiation absorbed by the cell at incidence angle \(\theta\) (\(\tau(\theta)\)) divided by the radiation absorbed at normal incidence (\(\tau(0)\)) [26].

\[
IAM (\theta) = \frac{\tau(\theta)}{\tau(0)}
\]

\(\tau(\theta)\) can be calculated by Equation 3.15 which is based on Snell’s and Bougher’s Laws [43].
\[ \tau(\theta) = e^{-(KG/\cos(\theta_r))} \left[ 1 - \frac{1}{2} \left( \frac{\sin^2(\theta_r - \theta)}{\sin^2(\theta_r + \theta)} + \frac{\tan^2(\theta_r - \theta)}{\tan^2(\theta_r + \theta)} \right) \right] \] 3.15

Here, \( K \) is the glazing extinction coefficient, \( G \) is the glazing thickness and \( n \) is the refractive index. In this study, \( K = 4 \, \text{m}^{-1}, G = 2 \, \text{mm}, \) and \( n \) is 1.526 for glass. The angle of refraction \( (\theta_r) \) is also determined from Snell’s law [26]:

\[ \theta_r = \sin^{-1}(n \times \sin(\theta)) \] 3.16

Above analysis applies only to the beam component of solar radiation. Radiation incidence on an array also consists of diffuse radiation from the sky. In general, the amount of diffuse radiation received by solar cells can be calculated by integrating the transmitted radiation over all angles, but the angular distribution of this radiation is generally unknown [43].

For simplification, an equivalent angle for diffuse radiation is defined and used in the same incidence angle modifier (IAM) for diffuse radiation. We call this angle; the angle of visibility (AOV). Since only the top shade is often fully exposed to the sun and part of the lower ones can be blocked by upper shades, the angle is defined as the half of the angle between the horizon and the line from the center of the shade to the tip of the upper shade plus the angle between the normal to the surface and the line from the center of the shade to the tip of the upper shade as shown in Figure 3-9.
Figure 3-10: Angle of visibility (AOV) for calculating the reflection losses for diffuse component of solar radiation.

While clearly the region of the shade closer to the window will receive a smaller amount of light and the region closer to the tip will receive a large amount, using the center of the shade provides an acceptable approximation of the average level of diffuse light on the panel as a whole.

3.5 Cell efficiency

Besides the material and design parameters, there are various environmental factors that can affect the PV cell’s efficiency. Some of the most significant factors are cell temperature, wind speed, and radiation intensity which are discussed in the following sections.

3.5.1 Cell efficiency vs. cell temperature

As cell temperature increases, cell efficiency decreases as well [44]. Cell temperature depends on the incoming solar irradiance, module’s electrical, optical, and thermal
properties. The PV performance modeling software (PVsyst) [45] implements a cell temperature model based on the Faiman’s module temperature model [46] which calculates the cell temperature with the following equation:

\[
T_c = T_a + I_{POA} \frac{\alpha (1 - \eta_m)}{U_0 + U_1 \times w_s}
\]

where, \(T_c\) is the cell temperature (°C), \(T_a\) is the ambient temperature, \(\alpha\) is the absorption coefficient of the module (PVsyst default value is 0.9), \(I_{POA}\) is the incident irradiance on the plane of the array (W/m²), \(\eta_m\) is the efficiency of the PV module, \(U_0\) is the constant heat transfer component (\(U_0 = 15\) W/m² K), \(U_1\) is the convective heat transfer component (\(U_1 = 0\) W/m³ s K) and \(w_s\) is the wind speed (m/s). Figure 3-10 shows the ambient temperature and wind speed variation in London during a year [35].

![Figure 3-10: Ambient temperature and wind speed variation in London.](image)

**Figure 3-10: Ambient temperature and wind speed variation in London.**

As mentioned before, if the cell temperature surpasses the standard test condition temperature (\(T_{stc} = 25^\circ C\)), cell efficiency (\(\eta\)) decreases with the following linear relation [38].
\[ \eta = \eta_c - (T_c - T_{stc}) \times 0.005 \]  

where, \( \eta_c \) is the cell efficiency at standard test condition temperature \( T_{stc} \).

### 3.5.2 Cell efficiency vs. radiation intensity

Solar cells efficiency generally is improved with the increase in levels of light intensity, and can be significantly reduced under low intensity. Reich et al [47] determined an empirical relation between PV efficiency and irradiation. Although the decrease in the solar cell efficiency towards weak light is very dependent on the cell technology, they calculated solar efficiency at different radiation intensities for various types of solar cells. We used their data for crystalline silicon panels to derive a fit to the following relation between efficiency and radiation intensity (Equation 3.19). Figure 3-11 displays the variation of cell efficiency with the change in light intensity.

\[ \eta = 0.19878 \times I_{POA}^{0.3008} \]  

**Figure 3-12:** Cell efficiency (\( \eta \)) variation with different radiation intensity, data points are reproduced from Ref. [47].
3.6 Sunlit area

In order to calculate both the amount of electricity produced by solar shades and heat passing through the windows, it is necessary to calculate the area of both windows and shades which are exposed to direct and diffuse intensities calculated above.

3.6.1 Windows

The areas of the windows exposed to direct and diffuse light change during the day with respect to the sun’s position in the sky. Some areas of the windows receive only diffuse light and the other areas receive both. In the next part, the exposed areas to both direct and diffuse light are formulated.

3.6.1.1 Direct area

Figure 3-12 illustrates the area of the window surrounded by two shades. $X_1$ is part of the window which receives direct and diffuse light together. Since zenith angle ($\varphi$) changes every hour, the $X_1$ will not be constant and changes in every time step.

Figure 3-13: Window area exposed to both direct and diffuse light with respect to the sun’s position in the sky.
To calculate $X_1$, Equation 3.20 can be used.

$$X_1 = H - (L \times \cos \beta) - \frac{L \times \sin \beta}{\tan \psi}$$  

where, $L$ is the length of the shade and $H$ is the space between each shade.

### 3.6.1.2 Diffuse area

Since diffuse light equally arrives from all sky directions, the area of the window which has the sky view is the diffuse area ($X_2$). In this case, $X_2$ is not dependent to the sun’s position in the sky and it is only function of sunshade angle ($\beta$), which determines the exposure to the sky as shown in Figure 3-13. \(Xi\) is an element of $X_2$ receiving diffuse light in a range of angles between horizon and tip of the top shade.

**Figure 3-14: Window area exposed to diffuse light with respect to the shade position.**

$X_2$ can be calculated with the following equation.

$$X_2 = H - (L \times \cos \beta)$$  

3.21
3.6.2 Sunshades

In this section, direct and diffuse areas of the shades will be calculated.

3.6.2.1 Direct area

As seen in Figure 3-14, some areas of the shades are blocked by upper shades at different times of the day. Therefore, the area of shades exposed to direct and diffuse light ($X_3$) is not constant and changes with each time step.

![Diagram showing calculation of direct area with symbols $H$, $\beta$, and $\phi$]

Figure 3-15: Sunshade area exposed to direct and diffuse light with respect to the sun’s position in the sky.

To calculate $X_3$, the area exposed to the direct light, Equation 3.22 is used.

$$X_3 = H \times \frac{\tan\phi}{\tan\phi + \tan\beta} \times \frac{1}{\cos\beta} \quad \text{3.22}$$
3.6.2.2 Diffuse area

Similar to the diffuse area of the window, the diffuse area of the shade ($X_4$) is only related to the sunshade angle. As the angle $\beta$ increases, the diffuse area of the shade increases as well. Figure 3-15 displays a schematic of this area.

Equation 3.23 calculates $X_4$:

$$X_4 = L - \frac{L \times \cos \beta - H}{\cos \beta}$$

3.7 Energy analysis

After calculating the amount of solar radiation received by windows and shades and their areas exposed to that radiation, we can calculate how much energy is produced (converted) or received. There are three forms of energy which are going to be discussed: electricity, heat, and light.
3.7.1 Electricity

Generating electricity is one of the main roles of BIPV sunshades. To calculate the produced electricity, it is necessary to have the exact area of the panels receiving radiation (direct or diffuse), radiation intensity per meter square of panels, absorption factor, and efficiency. Equation 3.24 determines the amount of electricity production by panels ($E_{gen}$).

\[ E_{gen} = n_s \times area_s \times I_{POA} \times \eta \times abs_s \]  \hspace{1cm} 3.24

where, $n_s$ is the total number of shades, $area_s$ is the total area of each panel receiving diffuse and direct light, and $abs_s$ is the absorption factor of solar cells which is taken to be 95%.

Since all these parameters change by time (except absorption factor), electricity generation by solar panels changes every time step too.

3.7.2 Heating

To calculate the amount of heating energy passing through the windows, we need to know the radiation intensity on the windows, the area of the windows exposed to the sunlight, and the transmission factor of the glasses on the windows. All of these parameters come together in Equation 3.25 to calculate heating energy every time step.

\[ H_{gen} = n_w \times area_w \times I_{POA} \times T_w \]  \hspace{1cm} 3.25

In this equation, $area_w$ is the total exposed area of each window, $n_w$ is the number of windows, and $T_w$ is the transmission factor of the window which is taken to be 95%. This heat transmission can be either desirable or undesirable depending on the season, which is incorporated in the value functions below.

3.7.3 Lighting

Studies of lighting in buildings have shown that working in a carefully illuminated environment is more comfortable and productive. High-quality lighting helps eliminate distractions, supports interaction and communication, contributes to occupant's well-being, and reduces health problems [48]. In addition, access to natural light has a positive
effect on human health and behavior. For instance, it is been demonstrated that access to sufficient natural light improves the healing process in hospitals and improves students’ performance at school [49].

The light that comes through the windows consists of two parts: beam (direct) light and diffuse light. While diffuse light is desirable, beam light causes glare, which is undesirable. In that case, sunshades have to be designed in a way that allows enough diffuse light into the room, while preventing excessive beam light to reduce glare.

Calculating the amount of natural light coming from windows is similar to calculating the heat, but beam ($L_b$) and diffuse light ($L_d$) are calculated separately.

\[
L_b = n_w \times \frac{I_b \times area_{w-b}}{area_{office} \times 0.0079} \tag{3.26}
\]

\[
L_d = n_w \times \frac{I_d \times area_{w-d}}{area_{office} \times 0.0079} \tag{3.27}
\]

$area_{w-b}$ and $area_{w-d}$ are window areas exposed to beam and diffuse light, respectively. $area_{office}$ is also the total area of the space. 0.0079 is the approximate conversion coefficient of $lux$ to $\frac{W}{m^2}$ ($1\ lux = 0.0079\ \frac{W}{m^2}$) and is explained below.

### 3.8 Optimization method

We use a stochastic Monte Carlo optimization method [50] to find the best combination of angle, length, and quantity of shades for each window. The reason to choose Monte Carlo method is its simplicity and low computational cost. This method generates random sets of numbers for design parameters in every iteration until it converges to optimum results.

We define four different value functions to use for optimization. Each value function can be used as a criterion for optimization alone, or in combinations together. For instance, if we want our system to be optimal at producing electricity, the optimization should determine the design parameters that maximize the power value function. In the following sections, each of these value functions is explained.
3.8.1 Power value function

Power value function ($PVF$) is defined as the amount of electricity produced by panels during a year. This is simply the summation of $E_{gen}$ in every time step (every hour) during the year. This corresponds to the total electricity, in kW, produced by the system.

$$PVF = \sum_{1}^{8760} E_{gen}$$  \hspace{1cm} 3.28

3.8.2 Heat value function

Similar to the power value function, heat value function ($HVF$) is also the summation of heat passes through windows every time step ($H_{gen}$, Equation 3.29). However, while generating electricity is always desirable, coming heat through windows is only preferable on cold days of the year (fall and winter). In summer, on the other hand, we need shades to block sunlight coming through windows as if heat comes into the building through windows in these days, it will likely need to be removed by the building’s cooling system. We take into account this negative effect with a coefficient we call “Heat coefficient”. It is the inverse of the coefficient of performance (COP) of a heating or air conditioning system. The heat coefficient is negative on hot days when ambient temperature is more than 20°C and heat coming into building increases the cooling load and impacts the performance. On cold days of the year, when the ambient temperature is less than 18°C, it is preferable that shades let heating energy into the room, and therefore, the coefficient will be positive. If the temperature is between 18°C and 20°C, the heat coefficient will be zero as incoming heat is neither particularly desirable nor undesirable. Figure 3-16 displays the variation of heat coefficient during the year. Note that the coefficient also goes to zero during any night hours when the system is not having any effect.

$$HVF = \sum_{1}^{8760} \text{coef}_{heat} * H_{gen}$$  \hspace{1cm} 3.29
Figure 3-17: Hourly variation of heat coefficient during a year. Inset 1 shows the transition from heating being beneficial to detrimental, as well as the day/night cycle in June.

3.8.3 Light value function

According to LEED® standard, the favorable range of light in an office environment is between 300 lux and 3000 lux. In the SI system, lux is the unit of illuminance and is equal to one lumen per square meter. For fluorescent lighting, this corresponds to roughly \(0.0079 \frac{W}{m^2}\). To calculate the light value function (LVF), it is essential to determine the amount of direct and diffuse sunlight coming through the windows. Since we assume diffuse light is always preferable and direct light is always undesirable (due to the production of glare), we define separate coefficients for diffuse and direct light. As seen in Figure 3-17, the diffuse light coefficient is always positive and equal to 1 if the diffuse light is more than 300 lux in the room. On the other hand, the direct light coefficient is always negative and decreases linearly with the amount of illuminance caused by direct light and is equal to -2 if the direct light is more than 3000 lux in the space. These values are chosen so that the optimization will still penalize large amounts of direct + diffuse light passing through the window. Another coefficient called “natural-artificial coefficient” (\(\gamma\)
is also defined which corresponds to how much we value natural light vs. artificial light. The light value function \( (LVF) \) is thus defined with the following equation.

\[
LVF = \gamma \times (\text{coeff}_{direct} + \text{coeff}_{diffuse}) \times \text{mean power usage} \times \text{area} \tag{3.30}
\]

where, \( \gamma \) is assumed to be 3, \( \text{mean power usage} \) is the average amount of power needed to light a space with no natural light and for an office room is around \( 2.5 \frac{W}{m^2} \).

![Figure 3-18: Diffuse and direct light coefficients in different illuminance.](image)

### 3.8.4 Overall value function

To find the optimum design parameters, we can use any of the three above value functions, but if we want to have more comprehensive results that include power, heat and light together, we define the overall value function \( (OVF) \) which is the combination of those three value functions. These value functions can be all added because they are all in units of \( \frac{kw}{year} \). The overall value function is based on the price of the electricity to allow easier comparison to the other costs of the system like the price of the equipment.

\[
OVF = (PVF + HVF + LVF) \times \text{price} \tag{3.31}
\]

\( \text{price} \) is assumed 0.13 \( \frac{\$}{kWh} \) and the unit of \( OVF \) is in \( \frac{\$}{year} \).
In the next chapter, we talk about the Cornerstone Architecture case study and discuss the results of the model in two different types including static and dynamic model.
Chapter 4

4 Static Model

In this chapter, we investigate the static model in both horizontal and vertical configurations. The model will provide optimal design parameters including length, number, and angle of the shade which will be constant during a year. First, we apply the model for a sample case, then we discuss the results of the model applied to the case study.

4.1 Horizontal layout

There are two typical configurations of BIPV sunshades, corresponding to either horizontal or vertical orientation of the shades. Horizontal layout is the most commonly used configuration in the buildings and in most cases, it is the most efficient configuration to design a BIPV sunshade system [30]. In this section, we explore the implementation and results of a horizontal layout in the model.

4.1.1 Simple case

In the first part of this study, we apply a detailed assessment of a simple case-study corresponding to a square $5 \times 5 \ m^2$ room with no obstructing surroundings, and with one south-facing window with the area of $1 \times 1 \times \ m^2$ in London, Ontario ($42.98^\circ \ N, 81.24^\circ \ W$).

We assume the solar cells used on the shades are similar to single-sided monocrystalline silicon cells currently available on the market with an efficiency of 20% and absorption of 95%. We optimize the system to maximize the overall value function and calculate associated design parameters. We then compare these results to the optimal configuration from other value functions. At the end of this section, we compare the south-facing window results to those of an east-facing window to elucidate the effect of window orientation.

4.1.1.1 Design parameters

We run the optimization for the simple case with different optimization criteria. The code generates stochastic combinations of design parameters for a set number of iterations and the configuration with the highest overall value function is the optimum configuration. In
the following figures, we discuss value function variations in different values of design parameters.

4.1.1.2 Overall value function

Figure 4-1 displays the variation of the overall value function in different sets of design parameters for 100,000 iterations. Figure (a) shows the variation of the overall value function with the number of the shades. As seen in the figure, using 4 shades on the window with even space between them achieves the maximum overall value function ($106.4$) during a year when the angle is constant. As the number of the shades increases, the amount of overall value function decreases. One reason is that having more shades lets less light and heat into the room. The other cause is self-shading of the panels - upper panels block the direct sunlight to the bottom ones, especially when the sun is high in the sky. Therefore, only a front part of the solar cells on the bottom shades will receive both direct and diffuse light, and as a result, their electricity production would be reduced. This effect becomes increasingly severe, as the cell efficiency falls with decreasing average illumination as well (Equation 3.19).

The second design parameter is the angle between the window and shade ($\beta$) which is displayed in the figure (b). We observe that the most efficient way that shades can be oriented is normal to the window ($\beta = 90^\circ$). As the angle between shade and window increases, the overall value function increases too, until it reaches its maximum value at the vertical position to the window. Although panels generate more electricity at smaller angles, the room receives less diffuse light and heat than shades oriented normal to the window. Therefore, the overall value function is reduced due to the cold climate of London.

The third design parameter is the length of the shade. Figure (c) illustrates the overall value function for different lengths of the shades. Due to the availability of the solar panels in the market and structure limitation, we limit the maximum possible length of the shade to 50 cm and as seen in the figure, the optimum length of the shade for the simple case in London, within the limitation of 50 cm is 42.7 cm. The associated value function of this point is slightly higher due to the stochastic simulation and we can see that the overall value function of shades with longer length is close to maximum as well.
Figure 4-1: Optimum (a) quantity, (b) angle and (c) length of the shades and their associated overall value function for the simple case with a south-facing window (red line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

4.1.1.3 Power value function

Figures 4-2 displays the amount of power generation in different sets of design parameters. According to Figure (a) and (c), the optimal number and length of the shades calculated above (4 shades, 42.7 cm long), are the best answer to generate maximum electricity as well (124.8 kW). We can see that as the lengths of the shades increase, there are more solar cells and the power generation increases too, but due to the self-shading effect of shades, there is an optimum point for the length and the maximum possible length is not going to have the maximum power generation.
Although 4 shades with the length of 42.7 cm are the best answer to maximize both overall and power value functions, the calculated angle of the shades is not able to maximize both. So, if the objective of the optimization is producing the maximum amount of electricity, shades should be positioned at the angle of 59° instead of normal to the window. Figure (b) displays that if $\beta$ is 59° the solar panels would generate 124.8 kW of electricity, while at 90°, electricity production is 103.8 kW during a year. In the previous chapter, we investigated the variation of zenith angle for London during a year (Figure 3-6), and we saw the sun would never be fully normal to the surface even in the middle of the summer. Therefore, it can be concluded that to maximize the power generation, solar panels must be oriented at an angle less than 90°.

Figure 4-2: Optimum (a) quantity, (b) angle and (c) length of shades and their associated power value function for the simple case with a south-facing window.
line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

4.1.1.4 Heat value function

After investigating the amount of power generation with different values of design parameters, we explore the variation of the heat value function with different design parameters (Figure 4-3). It can be seen from the figure (a) that the optimum quantity of shades (four) does not result in the highest heat value function. As the number of shades increases, more sunlight is blocked and less heat can come through the window; therefore, the heat value function decreases. Figure (b) and (c) also show that using shade with minimum possible length in any angles is the best configuration to maximize the heat value function. In other words, the code suggests that not using shades on the window is the best strategy if the goal is purely maximizing the heat value function; even though we can see from the figure that our optimum design parameters determined by the overall value function (4 shades with the length of 42.7cm oriented at 90°), still results in an acceptable amount of heat value function. It should be mentioned that this result is due to the heating vs cooling needs of our chosen location (London, Ontario) and it would be different for other locations with different climates. For instance, in a location with a hot climate using shades might be the optimum answer that would block the extra heat gain and reduce the cooling load.
Figure 4-3: Optimum (a) quantity, (b) angle and (c) length of the shades and their associated heat value function for the simple case with a south-facing window (red line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

4.1.1.5 East-facing window

In this part, we change the direction of the window of the simple case to the east. All the other assumptions stay the same. In Figure 4-4, we can see that the optimum configuration is similar to the configuration with a south-facing window (4 shades with the length of 42.7cm oriented at 90°), but the maximum overall value function is 7.1% less ($98.8).

In addition to the overall value function, maximum electricity production by east-facing shades is less than south-facing. In the east-facing arrangement, maximum electricity
production during the year is 88.8 kW which is 40.54% less than maximum electricity production in the south-facing system.

Figure 4-4: Optimum (a) quantity, (b) angle and (c) length of the shades and their associated overall value function for the simple case with an east-facing window (red line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

In the next part, we optimize the configuration of the shading system with two windows in different directions.

4.1.2 Simple case with multiple windows

To make the model more general, we add another window in a different direction to the simple case. Now, the simple case has two windows with the same size, one facing south
and the other one facing east. All other assumptions are the same as previous optimizations. Below, we calculate the optimum design parameters, and the value functions of both south and east windows and compare them with each other. When the simple case has two windows in different directions (south and east), the optimum angle would be $85^\circ$, as seen in Figure 4-5, while it was $90^\circ$ when the room has one window in either direction.

**Figure 4-5:** Optimum (a) quantity, (b) angle and (c) length of the shades and their associated overall value function for the simple case with two windows facing south and east (red line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

The reason of this reduction in the angle $\beta$ is the increase in the number of the windows and as a result, an increase in the lighting level of the room. Therefore, to keep the
lighting level of the room in a comfortable condition, it is needed to reduce the amount of direct light coming to the room by reducing the angle $\beta$. However, the quantity and length of the shades are the same with results calculated by optimization with one window in the south or east direction (4 shades with the length of 42.7 cm).

4.2 Vertical layout

Vertical layout is another configuration of sunshades and it is mostly common on east or west direction windows (Figure 4-6). In this part, we model the simple case with one window on the east side with vertical shades, and compare it with the horizontal layout.

![Figure 4-6: A schematic of vertical shades on east-facing window of the simple case.](image)

It can be seen in Figure 4-7 that the optimum configuration in vertical layout consists of 4 shades on the window with the length of 42.3 cm and the angle $\beta$ of 89°. The overall value function for this configuration is $82.96$ which is 20.9% less than the optimum configuration in the horizontal layout.
Figure 4-7: Optimum (a) quantity, (b) angle and (c) length of the shades and their associated overall value function for the simple case with vertical layout on the east-facing window (red line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

Figure 4-8 (a) shows the difference in value functions for both layouts for the east-facing window. While power and heat value functions are higher, the light value function is 36.89% less than conventional horizontal shades. Vertical shades receive more sunlight and they are less affected by self-shading than horizontal shades; therefore, they receive more heat energy and generate more electricity, but they are not performing as well as horizontal shades in blocking direct sunlight to reduce glare. This would result in less overall value function compared to the horizontal layout. Similarly, the horizontal layout for the south-facing window is more efficient than the vertical layout since the overall value...
function is 16% more. The comparison of other value functions for south-facing window is shown in Figure 4-8 (b). It can be seen that while horizontal shades generate less electricity than vertical shades in the east direction, they generate 2.41% more electricity than vertical shades facing south.

![Figure 4-8](image-url)

**Figure 4-8: Comparison of different value functions in horizontal and vertical layouts for (a) east-facing window and (b) south-facing window for the simple case.**

Light value function ($LVF$) is proportional to the room area (Equation 3.30), and as seen in Figure 4-8, it is relatively higher than other value functions because of the geometry of
the simple case. The area of the room is fairly larger than the size of the window which makes it have a better opportunity to keep the daylighting of the room in a comfortable condition rather than producing electricity or letting enough heat into the room.

4.3 Case study

The model was finally implemented for the conditions at the office of Cornerstone Architecture company, London, Ontario (43.98° N, 81.24° W), allowing a real case study to be performed (Figure 4.9). The Cornerstone Architecture office is located on the second floor of the building with the area of 380 $m^2$. The office has 10 windows in different directions; 7 south-facing windows, 3 east-facing windows, and also 4 west-facing windows which we do not consider in the optimization since they are under the patio. The area of each window is $3.6 \times 2.1 \, m^2$. To have a more suitable environment and a better view for employees, we separate 50 cm at the bottom of each window to not to be covered with any shades. Also, since working time at the office is between 8 am to 5 pm, the code only takes into account the negative effect of direct light or positive effect of diffuse light as well as the effect of heating (either positive or negative) in this period of time. The COPs of the heating and air conditioning systems of the office are estimated to be 2.

![The Cornerstone Architecture building locating on London, Ontario.](image)
Since the building is not facing direct south, we define a deviation angle ($dev$) which we calculate by simple geometric calculation using Google Earth satellite imagery (Figure 4-10). We determine that the building is about $20^\circ$ to the east and implement this inclination in the model.

![Figure 4-10: The Cornerstone Architecture building on Google Earth and calculating its inclination to the east ($dev$).](image)

On the south-west of the building, there is a tower with 60 m height which blocks the direct sunlight from reaching the building in a specific range of angles in the afternoon (Figure 4-11). To have a more accurate calculation of electricity production and incoming heat energy to the office, we find the exact location of the tower and the angles it blocks using Google Earth. We calculated that the direct sunlight is blocked by the tower when the zenith angle ($\phi$) is between $60^\circ$ and $90^\circ$ and azimuth angle ($z$) is between $40^\circ$ and $70^\circ$. 
Figure 4-11: Calculating the range of (a) zenith angle and (b) azimuth angle that the direct sunlight is blocked by the south-west tower.
4.4 Results

In this section, we discuss the results for the Cornerstone Architecture office as our case study for the model. We optimize the office with all of its windows (7 south-facing, 3 east-facing) and calculate all the value functions. We run the model for 100,000 iterations and select the iteration that generates the highest overall value function. Associated design parameters of that point (iteration) are selected as the optimum results.

4.4.1 Horizontal layout

First, we run the code to find the optimum design parameters assuming that the shades in both directions (south and east) are in horizontal layout. Then, we investigate the value functions associated with selected design parameters. In the next part, we change the layout of east-facing windows to vertical and compare the results with the conventional layout.

4.4.1.1 Optimum design parameters

As seen in Figure 4-12, the highest overall value function ($2,661) would be achieved if there are 5 shades on each window with the length of 49.8 cm and positioned at 90° to the window.
Figure 4-12: Optimum (a) quantity, (b) angle and (c) length of the shades and their associated overall value function in horizontal layout for the Cornerstone Architecture office (red line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

The results show that to maximize power generation, lighting condition is not going to be compromised. Figure 4-13 displays different iterations with their associated power + heat and light value functions. Each point represents a unique set of parameters and corresponding value functions.

We can see that those iterations generating maximum energy (electricity and heat) also have the highest light value function and this is the ideal design strategy for a BIPV system, but it depends on which one we value more, power or lighting. Power generation and heat flux are easy to quantify, but lighting quality is not and it depends on the user preference.
So, the potential for the trade-off between these means that different user preferences can lead to different optimal conditions. In our case, according to Figure 4-13, it is quite convenient to choose the optimal point, since there is a very narrow configuration space that optimizes both lighting and power + heat well.

As seen in the figure, point (a₁) is the most efficient point that has the highest power + heat value functions and light value function. However, if we value power production more than the lighting of the office, point (a₂) would be the ideal point. We can see that if the objective of the optimization is generating maximum power, the best point would be point (b), but it achieves less light value function than point (a₁). On the other hand, if it is desired to have the best possible lighting condition, we should select point (c), but it is not able to generate power as much as point (a₁).

Figure 4-13: The trade-off between heat + power value functions and light value function for different iterations in horizontal layout for the Cornerstone Architecture office.

So far, we ran the optimization for both east and south side windows together. We also optimize east and south windows separately. The results of separate optimization show that the overall value function is 3.29% less than optimizing both directions together. In this
case, the optimum number of shades for the south windows is 3, while using 6 shades on the east windows is optimal due to the poor performance of the east windows in illumination of the office. We can see that the optimum number that we calculated in the previous optimization (5 shades on each window in both directions) is the middle number between separate optimizations of east and south to compensate the poor lighting performance of the east-facing shades.

4.4.2 Vertical layout

In the simple case study for the east-facing window, although vertical shades did not work very well in controlling the lighting condition, they produced more electricity and received more heat energy than horizontal shades. In the Cornerstone Architecture office, since we have more and wider windows than the simple case, the difference in electricity production might be considerable. So in this section, we run the optimization assuming horizontal shades on the south-facing window and vertical shades on the east-facing windows of the office (horizontal-vertical). Then, we compare the results with the previous optimization with horizontal shades in both directions (all-horizontal).

4.4.2.1 Optimum design parameters

Since the dimensions of the shades are different when their layout is changed, we should analyze east-facing and south-facing windows separately.

Previously in Section 4.4.1.1, we saw that for south-facing windows, we need 3 horizontal shades on each window with the length of 49.8 cm at the angle of 90° to have the maximum overall value function ($1,908). For east side windows, Figure 4-14 illustrates that 12 shades with the length of 46.9 cm at the angle of 80° is the answer to achieve the highest overall value function ($654.9).
Figure 4-14: Optimum (a) quantity, (b) angle and (c) length of the shades and their associated overall value function for east-facing windows with vertical shades at the Cornerstone Architecture office (red line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

Similar to results from the simple case, vertical shades on the east side windows generate more electricity than horizontal layout, so the total electricity generation of the system is 9.08% more than the system with horizontal shades on the windows in both direction, but because of the poor performance of the vertical shades in illuminating the office with desirable lighting level, the overall value function is 3.82% less than all-horizontal layout. To have a better understanding of this point, Figure 4-15 displays the trade-off between light value function and power + heat value functions. In inset 1, we can see that if our optimization objective is just improving the lighting condition of the office, we should choose point (a) which produces the minimum amount of power and heat. This is
reasonable since the results also demonstrated that if our optimization objective is maximizing light value function, using no shades on the east-facing windows is the best solution.

Points in the area between two dashed lines are the most efficient points for vertical layout on the east-facing windows which produce a high amount of electricity and provide acceptable lighting level in the office. If we value lighting condition more than power and heat, we must choose points closer to line (b), but if our goal is generating maximum power, we should choose points closer to line (c). Unlike all-horizontal configuration that we had just four optimal points, all tightly clustered, here we have almost a continuum of points, meaning there is much more of a trade-off possible.

![Figure 4-15: The trade-off between heat + power value functions and light value function for different iterations for vertical shades on the east-facing windows.](image-url)

As we discussed above, we saw that there is not a big difference in the overall value function between all-horizontal and horizontal-vertical layout, and the main reason of this difference is that the light value function of all-horizontal case is higher than horizontal-vertical case. Figure 4-16 displays all value functions in the two cases. They are all converted to the unit of dollar to be added together.
4.4.3 Non-photovoltaic shades

Now that we conclude the horizontal layout is the most efficient configuration for both directions in the Cornerstone Architecture office, we analyze passive sunshades without solar cells on them, and then, we compare the results with BIPV sunshades. Passive shades do not generate electricity, but they block the direct sunlight and improve the interior daylight while protecting the interior environment from overheating [51].

4.4.3.1 Optimum design parameters

Results revealed that if sunshades are not able to produce electricity, the configuration of the shades would be different. Optimization results indicate that we need only one panel at each window with the length of 50 cm at the angle of 90° to maximize the overall value function (Figure 4-17). On the other hand, if we only care about the lighting condition of the office, we still need 6 shades with the length of 43.6 cm at the angle of 90°.
Figure 4-17: Optimum quantity of non-photovoltaic shades and their associated (a) overall value function and (b) light value function at the Cornerstone Architecture office (red line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

The trade-off between heat and light is shown in Figure 4-18. We can see that to achieve the best lighting condition in the office, we need a moderate number of panels on windows to block the direct sunlight while still allowing diffuse light, but that will reduce the heat value function (point (a)). If our objective is getting the maximum heating energy from the sunlight (especially on cold days of the year), the optimum solution is not using any shades on the windows (point (b)) and this would reduce the light value function. Therefore, the optimum answer is a point in the area between point (a) and point (b) which has a high overall value function. The optimization shows that given our standard assumption as to the value of lighting, this optimum point is a configuration with a 50 cm-shade on each window at the angle of 90°. The overall value function of this point is $2,194 which is only 0.8% more than the system with no shades on windows which suggests there is no point using shades on the windows, but people often do choose to use passive shades to avoid poor lighting conditions, so this suggests our model may actually be undervaluing lighting for many people currently. However, the entire outer surface connecting points (a) and (b) represent efficient solutions for different relative values of lighting quality.
Figure 4-18: Trade-off between heat value function and light value function of the non-photovoltaic shades for different iterations for the Cornerstone Architecture office.

It should be mentioned that while there is not a significant difference in overall value function between the optimum point (based on maximizing $OVF$, using one shade on each window) and not using any shades, the light value component of this optimum point is 11.51% higher than with no shades. This difference increases to 29.94% if the optimization is based on maximizing only the light value function (point (a)).

### 4.5 Validation of the lighting analysis

The office is simulated in Sefaira daylighting software by Cornerstone Architecture to compare the simulation results with our optimization results and validate the light value function of the model. The daylight analysis consists of three scenarios: no shades as a baseline, horizontal shades on south and east side, and horizontal shades on south side windows and vertical shades on east side windows.

The office was simulated with 6 horizontal shades on all windows for the second scenario. In the third scenario, it was 6 shades on south windows and 12 shades on east windows, with even space between them (32 cm) in both scenarios. This varies slightly from the
global optimum determined above, due to the inclusion of aesthetic considerations and preference of Cornerstone Architecture. The lengths of the shades in both scenarios are 45 cm and they are oriented at 87° to the windows, with a 50 cm unshaded region at the bottom of each window to ensure unobstructed views (Figure 4-19), similar to our optimization.

(a)  

(b)  

Figure 4-19: The Cornerstone Architecture office modeled in Sefaira software with (a) horizontal and (b) vertical shades on south and east windows.
4.5.1 Daylight analysis

The performed daylight analysis calculates two overall metrics, spatial daylight autonomy (sDA) and annual sun exposure (ASE).

Spatial daylight autonomy (sDA) is a metric describing the annual sufficiency of ambient daylight levels in the interior environments. It describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours. While larger values of sDA are preferable, with higher levels of daylight sufficiency, comes the potential for glare and solar heat gain [52].

Annual sunlight exposure (ASE) describes this potential for visual discomfort (glare) in the interior work environments. Specifically, ASE measures the percentage of floor area that receives 1000 lux or more for at least 250 occupied hours per year. Thus, the ideal lighting condition would have high values of sDA and low values of ASE [52].

In the first scenario, the office was simulated with no shades as a baseline for comparison. Figure A-1 (Appendix A) displays the spatial daylight autonomy and annual sunlight exposure of the office when there are no shades on the windows. The sDA of the office is 57% and ASE is 51%. While the ambient daylight level for the middle area of the office is acceptable, we can see that sDA near the windows is in the red zone and has a great potential for glare (figure (a)). As a result, 51% of the area receives more than 1000 lux (ASE) as displayed in (figure (b)). It can be seen that glare is too much in the window areas and is far from the pass checkmark (more than 250 occupied hours at 1000 lux). By comparing figures (a) and (b), it is apparent that without any shading device, nearly all of the sufficiently lit space also has unacceptable levels of glare. In the next part, simulation is done with shades on the windows to see their effect on the glare and lighting level of the interior.

In the second scenario, there are horizontal shades on the windows in both south and east directions. With shades on the windows, the sDA is decreased to 26% and as displayed in Figure A-2 (a), the areas near the window are in the yellow region which is after the pass mark and is acceptable. ASE is also decreased to 21% which is a significant improvement
compared to the first scenario with no shades (Figure A-2 (b)). It can be seen that there are now regions of the office with acceptable low levels of glare and sufficient daylight.

In the last scenario, the layout of the shades on the east side windows is changed to vertical to investigate its effect on the lighting level of the office. The area of the office that receives enough daylight is 1% less than all-horizontal shades (south and east) and now is 25% (Figure A-3 (a)). Moreover, vertical shades are not as successful as horizontal shades in reducing the glare, since ASE in this scenario is 22% which is 1% more than the second scenario with all-horizontal shades (Figure A-3 (b)). While similar in performance, both glare and daylighting are slightly worse in this vertical configuration.

The Simulation results support our optimization conclusion that all-horizontal layout would be more efficient than horizontal-vertical layout particularly in controlling the lighting level of the office (light value function).

To have a more accurate validation of the model, we run the model with the exact assumption of design parameters as simulated in the Sefaira software for all three cases. In the all-horizontal case, there are 6 shades on each window in both directions and there are 6 shades on the south and 12 shades on the east side windows in the horizontal-vertical case. The lengths of the shades are 45 cm and they are oriented at the angle of 87°. There is also a 50 cm view part at the bottom of all windows in both cases. Figure 4-23 displays the light value function of all cases. There is a 17.67% relative difference in the light value functions of the all-horizontal and horizontal-vertical cases that comes from the poor performance of the horizontal-vertical case in controlling the lighting condition of the office. The light value functions of all-horizontal and horizontal-vertical layouts are 29.26% and 14.08% more than that of no-shade case, respectively.

Although the light value functions are not directly comparable to the metrics produced by the Sefaira simulations, the trends are identical, which is a good indication that our model is still capturing the important trends in the more complex lighting analysis. This is also in agreement with Asfour’s research [28], which compared fixed geometry of horizontal and vertical shades, and concluded horizontal shades have better performance in general than vertical shades.
Figure 4-20: The light value function of all-horizontal, horizontal-vertical and no-shade cases with specific design parameters for the Cornerstone Architecture office.

4.6 Conclusion

In this chapter, we ran the static model for our case study and calculated the optimum design parameters to find the most efficient configuration for the BIPV shading system at the Cornerstone Architecture office. We observed that there is not a considerable difference between horizontal and vertical shades as in overall value function, and our objective of the optimization will decide on the final layout of shades. Although vertical shades on the east side windows generate more electricity than horizontal shades, they do not perform as well as horizontal shades in controlling the lighting level of the office.

In the next chapter, we investigate a time-varying dynamic model for our case study and discuss the results and compare them with the static model.
Chapter 5

5 Dynamic Model

In this chapter, we explore the dynamic model of our system. In previous chapters, all design parameters were constant during the year, but here, we investigate the performance of the system with time-varying angle. We define three different types of the dynamic systems. In the first, the angle of the shades changes every time-step (every hour) responding to the sun’s location in the sky to receive the maximum energy from the sun and simultaneously provide comfortable interior lighting condition. In the second, we find the best angle for every season, and in the third, the angle of the shades would be changed just twice, at the beginning and either the middle, or one optimized time in the year. The code calculates the optimum number and length of the shades for each scenario. The vertical layout is also investigated in these three dynamic systems.

At the end, we compare these three scenarios with each other and the static model from the previous chapter.

5.1 Changing angle every time-step

We begin by investigating a dynamic model where the angle of the shades can change every hour. First, the code runs every angle for a series of length/number of shades combinations, and choose the optimal angle for that combination every time-step. Then it finds the length/number combination that achieves the highest overall value function. We run the model for our case study with the horizontal layout for windows in both directions and other assumptions used in the previous chapter.

Figure 5-1 indicates that using 3 shades with the length of 50 cm on each window would bring the maximum overall value function for the dynamic system when the angle is changed every hour. By applying these calculated design parameters to our system, the value function would be $2,817 which is 5.52\%$ more than the overall value function when the angle $\beta$ is constant throughout the year (static model). Similar to previous studies [32], there is not a big difference in the overall performance of the static and dynamic systems.
Figure 5-1: Optimum (a) quantity and (b) length of the horizontal shades in dynamic system with changing angle every time step (red line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

Since the sun’s location in the sky is not constant and changes every hour, to gain the maximum overall value function, the angle of the shades (β) changes every time-step (every hour). Figure 5-2 displays the variation of the β during the year. Inset 1 shows the variation of the β during a day in the middle of the summer (July 18). It can be seen when the sun is at the horizon (in the sunrise and sunset hours), panels are almost closed and β is zero. As the sun goes higher in the sky, the panels become more open and the angle increases to receive more energy. In the middle of the day when the sun is in the highest location in the sky, β decreases to provide better lighting condition in the office. This variation of the β is less intense in the winter, partially due to a lower maximum sun angle as seen in inset 2, but it follows the same general pattern as summer days.

If the objective of the optimization is maximizing the electricity production instead of the overall value function which combines electricity, heat and light all together, the optimized design parameters would be different. The number of the shades would be 6 with the length of 43.6 cm to receive more sunlight and more power is produced.
Figure 5-2: Variation of the shade angle ($\beta$) during the year for the Cornerstone Architecture office. Inset 1 displays the variation of the $\beta$ in July 18 and inset 2 displays it in the period of Oct 22 – Nov 22.

### 5.2 Changing angle every season

Since automatic solar tracking systems add significant cost and system complexity, shades angle could instead be changed manually at specific times of the year instead of automatically every hour, if beneficial, at lower cost and complexity. In this part, we evaluate the system when the angle ($\beta$) is changed at the beginning of every season, winter (Jan 1), spring (April 1), summer (July 1), and fall (Oct 1). The code calculates the overall value function of every angle for a series of length/number combinations for each season, and chooses the optimal configuration considering the best angular performance at every season.
For this seasonal dynamic system, the design parameters would be 5 shades with the length of 50 cm. Results indicate that in the winter, spring and fall, the best angle would be 90°, similar to the static model, but in the summer (July 1), it should be changed to 76° and changed back to 90° after three months at the start of the fall (Oct 1). This would result in the overall value function of $2,750 which is only 2.45% less than changing the angle every hour, but still 3.21% more than the static system.

Figure 5-3: Optimum (a) quantity and (b) length of the horizontal shades in the dynamic system with changing angle every season (red line is an approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

The reason that $\beta$ needs to be decreased only in the summer is that sunshades have to be positioned at an angle which can block most of the heat energy from coming through the windows to reduce the cooling load of the office during hot days of the year. Since London has more days where incoming heat is a benefit than a detriment, we can see from the results that it is necessary to change back sunshade position to fully open (90°) after the summer (Oct 1) to be able to receive maximum heat energy from the sun.

In power-based optimization, the optimum design parameters are different. The optimum number of the shades is 6 with the length of 43.6 cm, the same as those with the hourly dynamic power-based optimization. The $\beta$ is also different in each season. Since in the fall and winter, the sun is lower in the sky and more toward the horizon, the panels must be at
a smaller angle to receive more sunlight. On the other hand, in the spring and summer, the sun is higher in the sky and panels must be more open to being exposed to the maximum sunlight. Therefore, $\beta$ is 57° both in the fall (1 Oct to 1 Jan) and winter (1 Jan to 1 April) and it is 81° and 90° in the spring (1 April to 1 July) and summer (1 July to 1 Oct), respectively.

5.3 Changing angle every 6 months

We next determine the optimal configuration when the angle of the shade ($\beta$) is changed only at the beginning and middle of each year (every 6 months). In order to gain the maximum overall value function if the angle is changed every 6 months (July 1) and changed back to the previous angle at the end of the year (Jan 1), we need 5 shades with the length of 50 cm on each window. But, surprisingly, optimization results revealed that if $\beta$ is changed once in the middle of the year, the system is not as efficient as the system when $\beta$ is 90° and constant during the year. Therefore, the third type of dynamic system would achieve the highest overall value function if the angles for both halves of the year ($\beta_1$ and $\beta_2$) are 90°. It is worth mentioning that since all optimum design parameters are exactly the same as the results in the static system, the overall value functions for both systems have the same values as well ($2,661.6$).

![Figure 5-4: Optimum (a) quantity and (b) length of the horizontal shades in the dynamic system when angle is changed in the middle of the year (red line is an](image)
approximate guide for the eye to show the maximum attainable performance for each individual design parameters).

So far, we saw that adjusting the shades in two different angles in each half of the year is not an efficient solution and we are better off adjusting the shades at the angle of 90° for the whole year.

This trend continues even when our optimization is based on maximizing the power generation. To produce the maximum electricity by solar cells in the third type of dynamic system, we need more shades on each window. However, in London, since the sun is not in the highest location in the sky on most days of the year, the shades must be in a lower position than fully open to receive maximum sunlight. The power-based optimization indicates that we need 6 shades with the length of 43.6 cm and both $\beta_1$ and $\beta_2$ would be 57°. We can see that even in this type of optimization and with the following design parameters, it is still more efficient to not change the angle in the middle of the year.

To investigate this issue more, we try to develop the model in order to calculate the best time of changing the angle to see if the problem comes from the timing of the change or its duration, because we already concluded that changing the angle during the summer (1 July – 1 Oct) is a more efficient strategy compared to constant model (Section 5.2).

5.3.1 Calculating the best time to change the angle

We try to find the best time to change the $\beta$ if system is capable of adjusting the angle once in a year. Interestingly, optimization results show that if the system is designed to change the angle of the shades at any time of the year and change it back to 90° at the end of the year (1 Jan), the system works no more efficient than the static system with the angle of 90°. Therefore, the model suggests the design parameters for the third type of dynamic system similar to the static system which results in the same overall value function with the static system as well ($\$2,661.6$).

This is likely because of the constraints on changing the angle on Jan 1, and that if both times were optimized, the outcome may be different. If the timespan is allowed to vary,
then we already know from the seasonal model that a system with two changes per year (during the summer, 1 July – 1 Oct) would have a better performance than the static system.

### 5.4 Vertical layout

We also modeled the dynamic version of the vertical layout (when shades on east-facing windows are vertical), but since we already concluded in the previous chapter that all-horizontal layout would have better performance (higher overall value function) than horizontal-vertical layout, we only briefly discuss the results here.

The overall value function of the first type of dynamic system (changing angle every hour) is 9.85% more than the static system when both of the scenarios have vertical layout on the east-facing windows. This difference for the second type (changing angle every season) is 6.22%, and for the third type (changing angle once in a year) is 1.9%. We can see that this is qualitatively different than all-horizontal model, where type three is equal to the static model, and unlike the all-horizontal layout, it is needed to change the angle of vertical shades on east-facing windows to 67° on Jun 6, and change it back to 90° at Jan 1, while the horizontal shades on the south-facing windows stay at 90° throughout the year. This contrast between two layouts (horizontal and vertical), comes from the fact the vertical shades on the east-facing windows do not perform as well as horizontal shades in controlling the lighting level of the office, especially at the beginning of the summer when the sun is higher in the sky.

In the previous chapter, we saw that the main reason for choosing all-horizontal layout as the more efficient configuration compared to horizontal-vertical layout was the poor performance of the vertical shades in providing comfortable lighting condition in the office. However, if shades angle ($\beta$) is changed every hour, the dynamic system with vertical layout can provide better lighting condition in the office and reduce the glare since the $\beta$ is changed with respect to the sun’s position in the sky. As a result, it is observed that the first type of dynamic system (changing angle every hour) has a slightly higher overall value function ($2,840$) which is 0.7% more than all-horizontal configuration.
5.5 Results

In this section, we compare the discussed models above with the static model investigated in Chapter 4. Figure 5-5 displays the overall value functions for the static and dynamic systems. We can see that if $\beta$ is changed every hour (the first type of dynamic system), the system would have the highest overall value function which is 5.52% more than the static system.

However, the difference between the first type and the second type is 2.45% which is likely negligible compared to the added cost and complexity of a solar tracking structure which changes the angle of the shades every hour.

Also, it can be seen from the figure that the second scenario, changing the angle for a three month period during the summer (July 1 to Oct 1), has an overall value function 3.21% more than changing the angle for a period of 6 months from July 1 to Jan 1 (and the equivalent static system).

Figure 5-5: The overall value functions for static and dynamic systems.
5.6 Conclusion

In this chapter, we investigated the dynamic version of the model to see its influence on the performance of the system. Although the hourly dynamic system would be ideal in that and it has the highest overall value function, the small increase in overall value function and much higher investment cost (dynamic structure cost) indicate that it is likely not worthwhile. Conversely, the seasonal model, where the sunshades angle can be changed manually from 90° to 76° in the summer may be still beneficial over the static system if the added cost and complexity of manual adjustment are minimal. It should be noted that all comparisons herein are specific to both the global location as well as details of the building investigated in this case study, but the general nature of the code developed here would allow similar analysis to be run for any other location of interest.
Chapter 6

6 Conclusions and Recommendations

In this chapter, we briefly review the results from our model and summarize the conclusions achieved in each chapter. The strengths and limitations of the project are then discussed, and the innovation of the work is highlighted. Finally, suggestions for the future work of this project are outlined.

6.1 Summary

This thesis focuses on the development of a model to optimize photovoltaic sunshade systems. We explore the use of our model on the design of shades for the south and east façades of the Cornerstone Architecture Company office in London, Ontario, as an example case study. Our objectives were improving daylighting and reducing glare by optimizing the angle and configuration of the shades on each window, reducing the heating and cooling loads, and generating electricity from the PV panels.

In Chapter 1, we motivated the need for PV shades, through realizing the net-zero energy building goals by integrating PV materials into building components, and the fact that with a multi-objective optimization, BIPVs can be used as external shading devices of buildings.

In Chapter 2, we reviewed the previous works done on similar systems, noting that all previous optimizations only focus on the energy-saving aspect of objectives especially daylighting, and did not consider the user preference in choosing trade-offs between each objective. Also, in all of their optimizing, at least one of the design parameters were held constant and others were optimized with respect to that parameter.

In Chapter 3, we outlined the development of the model, including the influences of the three-dimensional orientation of the sun relative to the shades, the time-varying intensity of direct and diffuse light, the influence of incident angle on light absorption, the decrease in cell efficiency with reduced insolation and increased temperature and the self-shading between louvers of the system.
In Chapter 4, we developed a static model where the angle of the shades ($\beta$) is constant during the year. In this section, we compared the horizontal and vertical layout of the shades and we optimized the design parameters (angle, number, and length of the shade). We saw that the best configuration for all-horizontal layout is 5 shades with the length of 49.8 cm at the angle of 90° to the window. If we change the layout of the east-facing windows to vertical, the final design parameters for south-facing windows would be 3 shades with the same length and angle, and for east-facing windows, it is 12 shades with the length of 46.9 cm at the angle of 80°. Although vertical shades on east side windows generate more electricity than horizontal shades, they do not block direct sunlight and therefore, they are unable to provide a comfortable lighting condition in the office. Consequently, our optimization results suggested that all-horizontal (horizontal shades on both south and east windows) layouts would be more efficient than horizontal-vertical (horizontal shades on south and vertical shades on east windows) layouts, due to the improved lighting outweighing the decreased power generation. At the end of this chapter, we also validated our results by qualitatively comparing them with the daylighting simulations of the office.

In Chapter 5, the dynamic version of the model was discussed. In the dynamic mode, the angle of the shade is not constant during the year. We divided the dynamic model into three types, corresponding to different frequencies of angle changes. In the first type, the angle $\beta$ is changed every hour to maximize the overall value function. The optimum number and length of shades in this type were found to be 3 and 50 cm, respectively. Although the first type of dynamic system achieved the highest overall value function, the dynamic structure to continually change the angle of the shades with respect to the sun’s position would be complicated and expensive. Accordingly, in the other two types, we investigated the possibility of changing the angle manually at specific times of the year to determine if the performance could still be improved. In the second type, we calculated the optimum $\beta$ for every season to maximize the overall value function in a year. In this condition, the optimum configuration was 5 shades with the length of 50 cm positioned at the angle of 90° in winter, spring and fall, and 76° in the summer. In the second type, the angle of the shades was changed every season instead of every hour, with an overall value function only 2.45% less than the fully dynamic system. In the last type, we saw that if our system is only
capable of changing the $\beta$ once in a year and changing it back at the end of the year (1 Jan), it would be most efficient to position the shades at the optimum angle of the static model ($90^\circ$) in the whole year. All optimization data are provided in appendices A to E.

6.2 Novelty of work

In this work, we combine all aspects of designing a BIPV shading system in a comprehensive way. This framework not only optimizes all of the design parameters of shading devices in a multi-objective optimization considering all forms of energy (power, heat and light), but also compares the performance of the static and dynamic systems in both horizontal and vertical configurations. Specific novelties of this study are discussed below.

One of the most important features of this work which has not been explored previously (to the best of our knowledge) is the detrimental effect of BIPV shading devices on heating load on the cold days of the year. Shading devices can reduce the heat gain and prevent the space from overheating in the summer, and as a result, this will reduce the cooling loads which will help in energy-saving of the system. However, this advantage of the shading system can turn into a negative effect on the heating loads in the winter, and this comes to great importance for locations in the northern hemisphere like London, Ontario, which has a colder climate than most regions investigated previously. Therefore, this dual effect of solar shades on the heating and cooling loads of the system needs to be considered in the optimization.

One of the critical aspects of this framework is that it optimizes all design parameters (number of shades, length, and angle) of the BIPV shading devices at the same time. Previous research studying the optimization of the BIPV shading devices can be categorized into three groups. The first group consists of studies that considered only a single shade above the window and optimized the angle and length of that shade [12, 14, 20-22, 28]. In the second group, the system had multiple shades on the window, but at least one of the three design parameters was held constant, and not considered in the optimization [15, 23, 24, 27, 32]. And the last group were the studies that investigated and compared the performance of different types of shading devices without optimization of
any parameters within the design [29-31, 34]. However, our framework can optimize all design parameters including angle, size, and number of both static and dynamic shades with any direction in horizontal and vertical layouts. The simplicity of the model we use here is largely responsible for the ability to perform this multi-parameter and multi-objective optimization.

Another novelty of this work which has not been explored in the majority of previous studies is the co-optimization of different forms of energy at the same time. Most of the previous works’ optimizations were based on the energy-savings of the system by considering the energy production of PV panels and cooling load reduction of the system. Even the limited studies that took into account the lighting control and visual comfort of the system in their optimization, investigated the lighting performance in terms of energy-savings, and did not consider any preference for natural light over artificial light. In our model, natural light is separated into diffuse and direct light and glare is calculated based on the incoming direct light through the windows, allowing the positive aspects of diffuse light to be included with the negative value of glare-producing direct light. We additionally include an estimated relative value of natural light over artificial light of 3, with evidence from our work indicating even this factor is close to a lower bound on this value.

Finally, our model takes into account the effect of variation of ambient temperature and wind speed as well as the variation of radiation intensity on the solar cell efficiency which has not been done previously (again, to the best of our knowledge). This has significant impacts on the amount of energy predicted to be produced by the PV panels, which thus shifts the optimized configuration due to the trade-off between power generation, heat, and lighting.

6.3 Strengths and limitations

This code is general and can be applied to different types of buildings with specific properties including the number, area, and direction of the windows in any location. Properties of solar materials also can be chosen by the user.
While our model optimizes the shade configuration based on the combination of all objectives (power generation, heating, and lighting), it is also capable of finding the best configuration based on each of the objectives separately. For instance, if the objective of the optimization is only maximizing power generation, the model can be tuned to optimize design parameters in a way to satisfy this objective. In other cases, controlling the lighting condition of the office and reducing the glare can be the main objective of the system, therefore, the optimum configuration of the shades would be in a way to provide the most comfortable lighting condition in the interior space.

In our work, sunshades are modeled and analyzed in two different layouts; horizontal and vertical, which can be either static or dynamic. Also, the effect of external factors such as surrounding obstacles, ambient temperature, wind speed, and radiation intensity variation, on the performance of the system are all considered.

Unlike the previous studies which their model could optimize only one layout for all directions (if their model was able to analyze multi directions other than just one), our model is able to optimize sunshades with different layouts (horizontal and vertical) and in arbitrary directions. However, this feature can bring about one of the limitations of our model explained below.

One of the most important limitations of the model is lighting analysis. Since the model cannot distinguish accurately how much area of the space is affected by windows in each direction, we specify a portion of the area to each direction linearly to the number of the windows in that direction. For example, when we optimize the horizontal shades on south and vertical shades on east at the same time, we need to calculate the light value function ($LVF$) of each direction separately. Since the amount of $LVF$ depends on light intensity and area (Equation 3.30), we need to have the corresponding area for each direction to calculate the associated $LVF$. Therefore, to keep the model simple and fast, we use this approximation that the number of windows in each direction has a linear relation to the area corresponding to that direction. For example, there are 7 windows in south and 3 windows in east direction, the areas that sunlight from south and east windows cover are 70% and 30% of the total area of the office, respectively.
It should be mentioned that in the thermal analysis, we only looked at radiation, while there are other influences that are clearly important like changes in conduction and convection. In particular, changes in convection is really important, but it will be extremely difficult to model accurately, so we left that out due to being outside the scope of the work and computational prohibitive. In fact, these factors should be considered before the final design of this work is implemented, especially because the effect of convection is hard to anticipate. For instance, it could channel the wind to the window and increases conductive heat transfer or it could create a buffer zone and decreases the conductive heat transfer. So, this factor needs to be studied in detail before actual shades are implemented. As a result, these are the reasons that we only look at radiative heat transfer.

The results obtained from the optimization were influenced by weather condition, properties and assumptions about the building (Cornerstone Architecture office), and obviously, in a warmer climate or in a location closer to the equator which solar radiation intensity is higher, the results of the optimization would lead to different configurations.

Another limitation of the dynamic model specifically is that the panels have only one degree of rotation. This however fits with the majority of commercial BIPV shades, which can be adjusted in at most one degree of freedom (due to complex and expensive structure).

Above all, the optimization process is much faster than full architectural lighting simulation software with similar results, because of the simple computational method used in this framework.

### 6.4 Future recommendations

In our model, we used a Monte Carlo optimization method due to its simplicity and low calculation cost. In the future, other optimization methods such as evolutionary algorithms or particle swarm optimization (PSO) could be applied in order to improve the search efficiency and thus reduce the computational time requirements. In our optimization, the running time for the static model with 100,000 iterations is around 30 minutes, and it is about one hour for the dynamic model with 2,000 iterations (as each iteration includes 90
angles). Other optimization methods should be able to decrease this running time, as they do not search all space evenly, which is worthwhile to investigate.

The methodology could additionally be further validated by comparing the outputs with data from experimental setups of the system in the laboratories and verifying the performance of the system in different locations. All of our results are specifically for the location of our case study, and optimization results will be different in other locations. In addition, multi-reflection of surfaces can be investigated by detailed modeling or experiments and results can be compared.

Also, this study can be further improved by investigating the non-homogenous tilt angle and spacing in the BIPV shading system. In that case, optimization of objectives such as power production, heating and cooling loads, and lighting condition would result in different configurations which can be compared to our results.
References


[52] I. LM, "Approved method: IES spatial Daylight autonomy (sDA) and annual sunlight exposure (ASE)," 2013.
Appendices

Appendix A: Daylighting simulation results.

Figure A-1: The (a) spatial daylight autonomy and (b) annual sunlight exposure of the Cornerstone Architecture office in the first scenario (no shades).
Figure A-2: The (a) spatial daylight autonomy and (b) annual sunlight exposure of the Cornerstone Architecture office in the second scenario (all-horizontal shades).
Figure A-3: The (a) spatial daylight autonomy and (b) annual sunlight exposure of the Cornerstone Architecture office in the third scenario (horizontal-vertical shades).
### Appendix B: Optimization data of the simple case in the static model.

<table>
<thead>
<tr>
<th>Simple case</th>
<th>East and south (horizontal)</th>
<th>South (horizontal)</th>
<th>South (vertical)</th>
<th>East (horizontal)</th>
<th>East (vertical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on maximizing overall value function ($OVF$)</td>
<td>$OVF ($)$</td>
<td>126.8025</td>
<td>106.4468</td>
<td>89.4472</td>
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<td>89</td>
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<td>0.4270</td>
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<tr>
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<td>0.4280</td>
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Appendix C: Optimization data of the Cornerstone Architecture office in the static model.

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<tr>
<th>Static model</th>
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<th>South (horizontal)</th>
<th>East (horizontal)</th>
<th>East (vertical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on maximizing overall value function ($OVF$)</td>
<td>$OVF ($)$: 2.6616e+03</td>
<td>$1.9086e+03$</td>
<td>665.2938</td>
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<td>Number</td>
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<td>0.4980</td>
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<td>Based on maximizing power value function ($PVF$)</td>
<td>$PVF (kW)$: 6.1330e+03</td>
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<td>Length (cm)</td>
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<td>0.4990</td>
<td>0.4360</td>
<td>0.4690</td>
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<tr>
<td>Based on maximizing power +heat value function ($PVF + HVF$)</td>
<td>$PVF + HVF$: 1.1458e+04</td>
<td>$9.6134e+03$</td>
<td>2.2380e+03</td>
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<td>12</td>
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<td>Length (cm)</td>
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<td>0.4920</td>
<td>0.5</td>
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<tr>
<td>Based on maximizing light value function ($LVF$)</td>
<td>$LVF (kW)$: 7.9924e+03</td>
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Appendix D: Optimization data based on overall value function of the Cornerstone Architecture office in the dynamic model.

<table>
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<th>Dynamic model (based on maximizing $OVF$)</th>
<th>East and south (horizontal)</th>
<th>South (horizontal)</th>
<th>East (horizontal)</th>
<th>East (vertical)</th>
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</thead>
<tbody>
<tr>
<td>Fully dynamic - changing angle every hour</td>
<td>$OVF ($$)</td>
<td>2.8174e+03</td>
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<td>Angle (°)</td>
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</tr>
<tr>
<td>Number</td>
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<tr>
<td>Length (m)</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>Changing angle every season (winter-spring-summer-fall)</td>
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<td>0.499</td>
<td>0.4680</td>
</tr>
<tr>
<td>Changing angle twice a year (every 6 month, Jan 1 – July 1)</td>
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<tr>
<td>Number</td>
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<td>Length (m)</td>
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<td>0.5</td>
<td>0.499</td>
<td>0.4680</td>
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<tr>
<td>Changing angle twice a year (Jan 1 – optimum day)</td>
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Appendix E: Optimization data based on power + heat value functions of the Cornerstone Architecture office in the dynamic model.

<table>
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<th>Dynamic model (based on maximizing $PVF + HVF$)</th>
<th>East and south (horizontal)</th>
<th>South (horizontal)</th>
<th>East (horizontal)</th>
<th>East (vertical)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>$OVF$ ($)</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Number</td>
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<tr>
<td>Length (m)</td>
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<td>0.5</td>
<td>0.499</td>
<td>0.4680</td>
</tr>
<tr>
<td>Changing angle every season (winter-spring-summer-fall)</td>
<td>$PVF$ + $HVF (kW)$</td>
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<td>90–90–8–90</td>
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<td>5</td>
<td>12</td>
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<tr>
<td>Length (m)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4990</td>
<td>0.4680</td>
</tr>
<tr>
<td>Changing angle twice a year (every 6 month, Jan 1 – July 1)</td>
<td>$PVF$ + $HVF (kW)$</td>
<td>1.2061e+04</td>
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<td>Number</td>
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Appendix F: Optimization data based on power value function of the Cornerstone Architecture office in the dynamic model.

<table>
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<tr>
<th>Dynamic model (based on maximizing $PVF$)</th>
<th>East and south (horizontal)</th>
<th>South (horizontal)</th>
<th>East (horizontal)</th>
<th>East (vertical)</th>
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</thead>
<tbody>
<tr>
<td>Fully dynamic - changing angle every hour</td>
<td>$PVF(kW)$  6.5310e+03</td>
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<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>Number 6</td>
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<td>6</td>
<td>12</td>
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<td>0.4980</td>
<td>0.4320</td>
<td>0.4680</td>
</tr>
<tr>
<td>Changing angle every season (winter-spring-summer-fall)</td>
<td>$PVF(kW)$  6.2841e+03</td>
<td>5.0379e+03</td>
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<td>Number 6</td>
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<tr>
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<td>Length (m) 0.4360</td>
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<td>0.4320</td>
<td>0.4680</td>
</tr>
<tr>
<td>Changing angle twice a year (every 6 month, Jan 1 – July 1)</td>
<td>$PVF(kW)$  6.1330e+03</td>
<td>4.7879e+03</td>
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<td></td>
<td>Angle (°) 57–57</td>
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<td>Length (m) 0.4360</td>
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</tr>
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</table>
Curriculum Vitae

Name: Seyedsoroush Sadatifar

Post-secondary Education and Degrees:
Ferdowsi University of Mashhad
Mashhad, Iran
2012-2016 BESc.
Ferdowsi University of Mashhad
Mashhad, Iran
2016-2018 MESc. (Transferred to University of Western Ontario)
The University of Western Ontario
London, Ontario, Canada
2019-present MESc.

Honors and Awards:

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Teaching Assistant
University of Western Ontario
2019-2020
MITACS accelerate program
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Proctor
King’s college, London, Ontario
Fall 2019
Teaching assistant
Ferdowsi University of Mashhad, Mashhad, Iran
2016-2018

Publications:
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