Dynamic Shading: An Analysis

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Abstract

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Efficient use of energy is vital. Electric lighting contributes to a significant part of the total energy use in the US. Efficient use of daylighting offers a significant reduction in overall energy use. However, because the light available changes dynamically; the design of static shading systems adhering to both high and low levels of light is difficult. This thesis explores dynamic shading systems and analyses the benefits of an adaptive system when compared to a static system. The main goal of the thesis is to analyze a dynamic shading system in different conditions and compare it with a static system; in order to establish the advantages and disadvantages both quantitatively and qualitatively in terms of daylighting. Unfortunately, most of the daylighting metrics are not developed with a dynamic system in mind. So the thesis will also look to utilize a metric which takes account of the dynamism. The analysis process developed in this research involves building a series of simulation models in Ecotect. Each model represents one physical configuration of the system. Using Radiance and DaySim, Annual Illuminance Profiles are computed consisting of "snapshot" simulations at hourly intervals for a specific city. Custom software written in Java for individual static positions processes these profiles and computes the metrics adopted. Further, an hypothesized Dynamic system is computed by combining the individual static positions. Finally, the behavior and benefits of the Dynamic system is evaluated by comparing the Static and Dynamic system results for different latitudes.

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Acknowledgements

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1.Introduction

“Adaptivity” means to interpret change in the environment and to respond to it. The very character of change is dynamism. Architecture designed for a static set of factors does not necessarily facilitate this adaptability to change. We have seen massive changes on the sustainability front in recent times, but the paradigm for designing performance based systems has not changed. To achieve the full potential of climatic response, the paradigm has to change. Conventional buildings are designed as static entities while they address dynamic factors like solar patterns and wind variation. This often creates a disjunction between the building and its environment. To address this disjunction we need buildings that can adapt to change, assimilating the information and learning from it. The systems need to respond dynamically to the changing environmental conditions thus providing better efficiency than static systems.

This thesis is an exploration into dynamic shading to achieve specific architectural goals. The goal would be to save energy in terms of daylighting by adopting an hypothetical dynamic system which adapts to the solar movements. In the future, this dynamic shading could be optimized to incorporate other dynamic factors like ventilation and site specific user patterns. User response is often neglected in adaptive systems. Though this thesis will not look into it in detail; it will try to raise the question in the case studies and allow freedom for future exploration to incorporate the user patterns along with the environmental data to drive the optimization process for adaptive structures. This thesis assumes that the site conditions remain static. Through the analysis, the performative aspects of the dynamic shading will be explored relative to those of a static system.

History of Adaptivity:


Figure 1 Mesolithic Stone Age House

Early man found shelter in caves and other structures existing in nature. In this age Man's adaptivity lay in his nomadic nature. They would move from place to place depending on the environmental factors. Migrations happened in response to changing environmental conditions. His movement gave the necessary adaptivity missing in the structures he lived. Eventually, nomadic nature made way to fixed built environments**.** Some of the first fixed houses made were cone shaped and wrapped in thatch (Figure 1). The adaptivity in these structures was through the porous skin. The thatch allowed the house to breathe even though it lacked any openings other than an entry door. Adaptivity through the hatch was a prominent feature in Mesolithic Stone age houses. Moving into the Neolithic age, Catal Huyuk was one of the first non-nomadic settlements (Figure 2). It was built around 6,500 BC. The houses were built right next to each other. There were no doors and houses were accessed through the roofs (Mellart,1967). The holes in the roof acted as an adaptive system for ventilation. It has to be noted that, around this time, safety was the main priority rather than comfort.

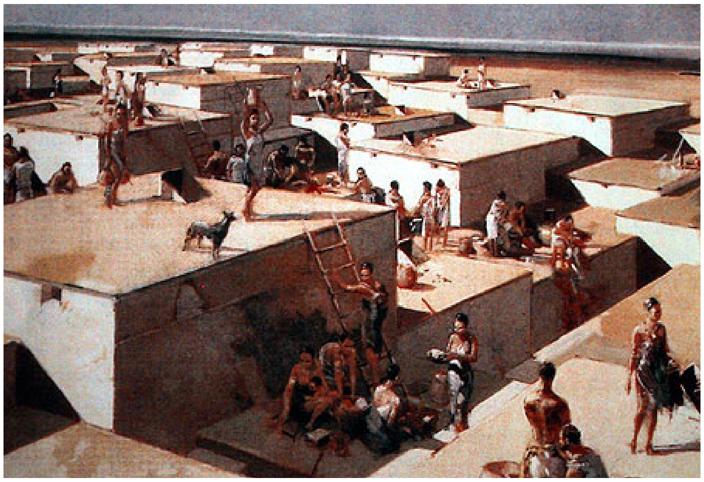


Figure 2 Catal Huyuk

The first sign of usage of doors is seen in Egyptian tombs. They had huge single or double wooden doors. The next sign of houses with doors is seen in the Middle East in Jericho and the Indus valley civilization where the houses made of brick had doors at the ground level (McIntosh,2008). Doors helped in adaptivity of ventilation and light and to control the environment within the space by enclosing the air drafts. A 5,000-year-old door was excavated by archaeologists in Switzerland which showed that use of doors as a system started a long while back (Jordan,2010). Use of Windows probably started in the Indus valley civilization (Figure 3). Primeval windows were only openings in a wall. Later, animal skin or wood were used to cover these openings. The use of shutters came later. The use of ventilation shafts probably started in the Indus Valley civilization. By covering shafts, they provided adaptivity to alter air currents.

These systems further evolved in the Roman period. Around 100 AD for better adaptivity, they were using sliding and folding doors with slotted rocks as tracks (Neuburger,1969). Around the same time period the Greek scholar Heron, who studied early forms of mechanical engineering, invented automatic door (Woodcroft,1851). The first use of glass in windows is also seen although they had poor optical properties. They also started the use of centralized heating systems by heating air under the floor using furnaces, known as hypocaust (Turner,1948). Around 2nd century AD, we see the invention of a rotary fan for air-conditioning in China. This is further developed in 7th century by using water powered fan wheels (Needham,1991). In 7th century AD, we see the first user specific control based adaptive system in the form of automatic door. (Needham,1991). A similar adaptive system was created by

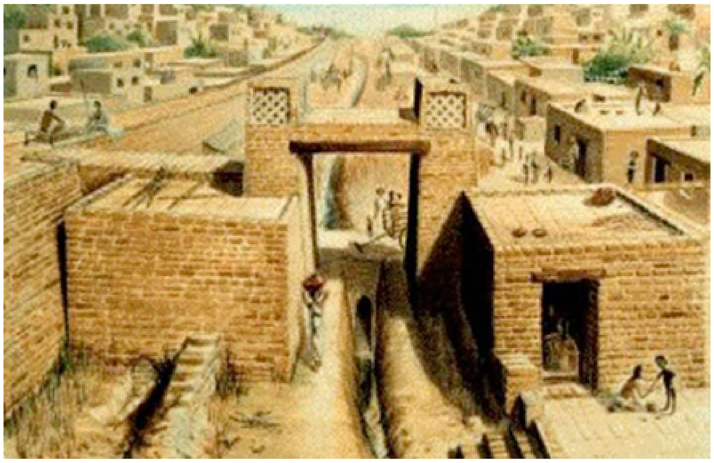


Figure 3 Reconstruction of Indus Valley Civilization

Arabic inventor Al-Jazari, who created an automatic gate operator in the 13th century (Turner,1997) (Figure 4).

The first hydrological based central heating system was seen in Russia in 18th century.. Centralized systems made buildings more adaptive to environmental conditions. Industrial Revolution had an enormous impact, and we see further modernization and higher efficiency of heating ventilation and air conditioning around that time. So all the systems we see now are following a paradigm which has been there for centuries, but somewhere down the line this evolution of adaptivity has slowed down. Spaces and systems designed for dynamic solar movement have become static and have not been taking advantage of technological advances. Fundamentally, a system designed for a dynamic set of factors like the sun and other environmental influences in the short term and immediate surroundings and user patterns in the long term should be ideologically dynamic and adaptive. To choose a system for analyzing in this thesis, it is essential to classify the adaptive systems.

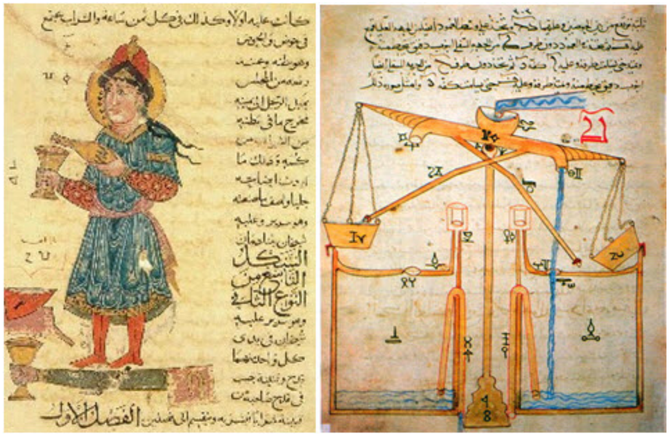


Figure 4 Automatic Gate, 100AD

2. Classification of Adaptive systems

Adaptivity systems are broadly divided into four different types based on the level of adaptivity (Adaptive Architecture,2011).

a) Dynamic Facades and Intelligent Surfaces

Sensor based Responsive architecture includes dynamic facades, communicative building fabric and intelligent independent surfaces. Most of the contemporary adaptivity is under this classification as it is easy to separate the functionality of the non-adaptive parts of the building from the adaptive parts.

b) Transformable Structures

This second category of adaptive systems involves entire buildings, which adapt over the longer term to altering demands, environmental patterns and other external factors. In this context, it is exceedingly easy to draw a parallel between a living species and a building. As a living species evolves over generations and morphs and adapts, the building itself should be able to do this over its life period. This adaptivity is yet to be realized in a larger scope as several economic, functional, technological challenges faced by the systems are yet to be resolved or realized.

c) Smart Materials

The third category consists of materials whose properties can be changed in a controlled manner by external factors such as temperature, magnetism or light. These can be considered as Smart materials. Though the progress made in the science of smart materials is dependent upon the advances in the material sciences largely, it is broadly considered that there is a large scope for impact on architecture on this front. The use of materials that alter their properties to external stimuli such as heat, moisture, or light can redefine how we comprehend Architecture. The key considerations in smart materials will be if the changes are reversible or irreversible. They could be as straightforward as paints which change color based on the temperature (Ritter, 2007).

d) System Intelligence

The final adaptivity category is that of System Intelligence, which can occur at two levels. The first level of system intelligence is the automated response of the building to the changing environmental conditions. Most modern adaptive buildings are competent at this level. The second level of system intelligence would be the system's response to the user and user patterns. The system itself should be ‘intelligent’ and ‘emergent’; capable of learning from the set of user responses taking into account future weather patterns and changing accordingly. In the long run, it should also have the capability of learning from mistakes made in the system. With the large number of available data streams, weather data from the past century can be used to forecast the future weather patterns. the centralization of the building systems which have been transformed by the ubiquitous communication technologies has given a tremendous scope in improving the building intelligence. To make use of the data and not only optimize it but also learn and evolve from the data is imperative to make efficient building systems.

We will look at different case studies under the above classification of adaptive systems.

3. Case Studies

Arab World Institute

Figure 5 South Façade

Location: Paris

Date: 1988

Architect: Jean Nouvel

Climate: Temperate

Building Type: mixed use, Cultural Centre

Adaptive System: Dynamic Façade, System Intelligence (lower level)

Arab World Institute is the one of first buildings to employ sensor based responsive architecture which has an automated response based on the environmental conditions. This treatment is on the south side (Figure 5) divided into 240 sub grids (Figure 6) which consist of photosensitive mechanical devices that act like automated irises to control light. There are 30,000 light sensitive diaphragms on 1600 elements, which function like, a lens of the camera. All the mechanical devices are connected to a central computer. Based on the light quality inside the building, the irises open or close incrementally. This screen is an interpretation of Arab latticework screens which are seen in patios and balconies of Arab countries. The main focus is on lines and play of light (Arab World Institute,1989).

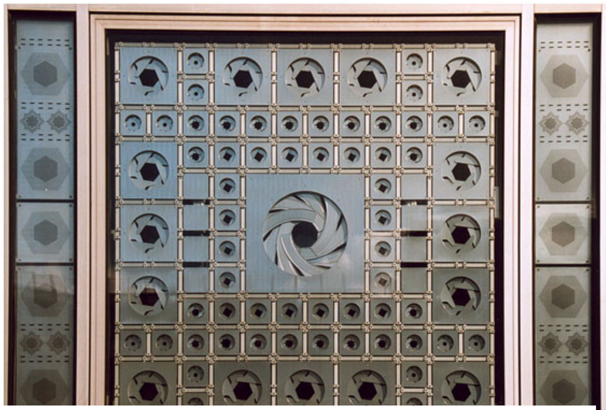


Figure 6 Sub grid, Irises

Observations

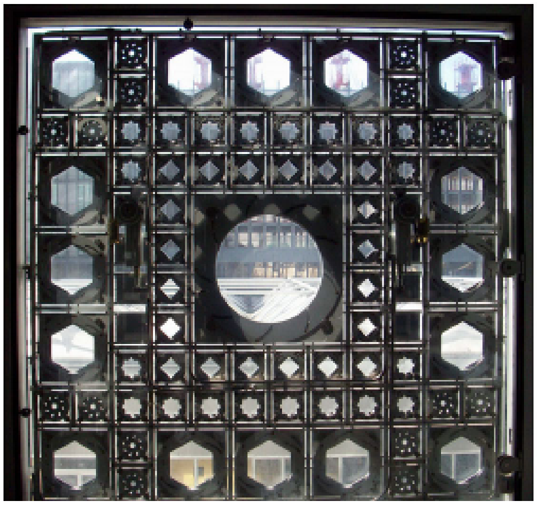


Figure 7 Sub grid, Irises

It is extremely essential to approach the adaptive systems with a strong conceptual basis. This keeps this building compelling even though numerous failures due to mechanical complexity and overly expensive maintenance has hindered the operation of this system. The building retains its charm as it has a strong conceptual intent based on Egyptian screens. So it is essential to approach adaptive systems with strong conceptual intent. On the other hand though this work is seminal in adaptive systems it highlights the real life problems with these experimental systems. So a strong thought should be given to the real life working of the system.

GSW Headquarters

Location: Berlin, Germany

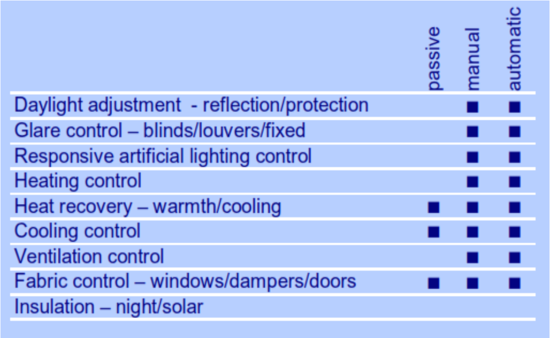
Date: 1999

Architect: Sauerbruch Hutton Architekten

Building Type: Office

Area: 54,000 Sqm

Adaptive System: Dynamic Façade, System Intelligence with occupant override



	passive	manual	automatic
Daylight adjustment - reflection/protection		■	■
Glare control – blinds/louvers/fixed		■	■
Responsive artificial lighting control		■	■
Heating control		■	■
Heat recovery – warmth/cooling	■	■	■
Cooling control	■	■	■
Ventilation control		■	■
Fabric control – windows/dampers/doors	■	■	■
Insulation – night/solar			

Figure 8 Building Management System

The striking design feature of the building, which is also the adaptive system of the building, is the façade (Figure 9). The east façade has triple-glazed windows with blinds in between the panes which can be operated automatically or manually. The west façade is dual-skinned with double pane windows on the inner side. They also can be operated both manually or automatically. On the west fa çade wide, vertical, perforated aluminum louvers

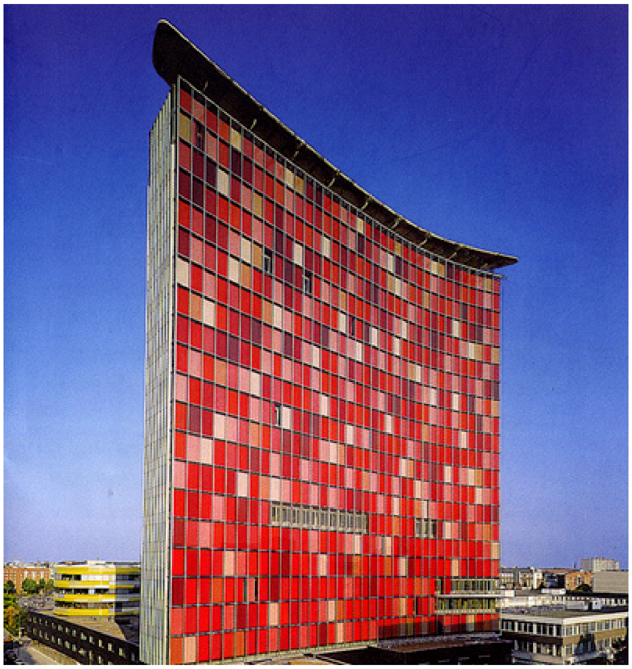


Figure 9 GSW Headquarters West facade

of various colors, ranging from ruby red to pink to orange, are located in this interstitial space which provides external solar shading. On sunny days, the colored elements complement one another into a colored carpet shading the entire west façade. The double glass on the West façade allows for a natural air conditioning through chimney effect caused by cross ventilation (Figure 10). This results in a 40% reduction of energy usage compared to German energy standards (Russel, 2000). This system controls the airflow by closing and opening the dampers at the top and the bottom and also controls the artificial lighting based on the daylight available. Artificial lighting is switched off if the day lighting is sufficient. This is a real time system. It also controls the colored louvers on the west façade automatically (GSW,2012) (Figure 12). Another important feature of the system is user specific control making provision for override. The users can override the system through zonal controls provided at all the window sill levels (Figure 11). While overriding, the Building Management System makes recommendations to the users about the selections they are going to make through red and green lights.

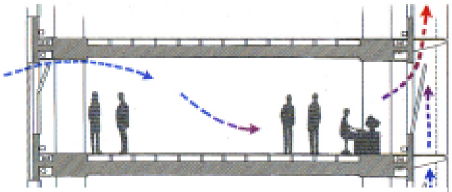


Figure 10 Cross Ventilation

Figure 11 User Override controls

Observations

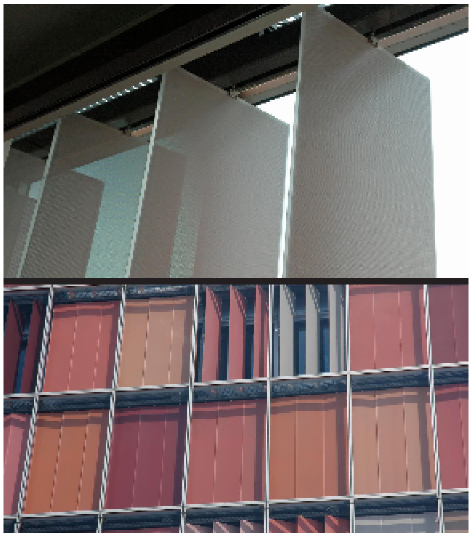


Figure 12 Automated Louvers

This is one of the few buildings which not only gives user specific override control over the automated building management but also gives feedback to the user while the override is made. Considering that this building was built 15 years ago, these user controls can be replaced in new buildings using mobile devices. This enables more freedom in the override process and also enables the system to give more detailed feedback on the decisions made by the user. This system is more advanced than the entry level system intelligence, but it does not have any emergent system which learns from the decisions made by the user.

Hoberman Arch

Figure 13 Hoberman Arch, Detail

Location: Salt Lake City, Utah

Date: 2002

Size: 35' tall, 72' wide

Architect: Hoberman Associates

Building Type: Installation

Adaptive System: Transformable Structure

The Hoberman Arch is a transforming curtain. The design of the Hoberman Arch was an intense collaboration between Hoberman Associates and Buro Happold. The screen is both a mobile mechanism and load-resisting structure. It is claimed to be the largest Transforming structure to date. It is made of 4000 individual pieces; connected together into 96 panels of varying sizes using 13000 rivets. The structure transformed through pulling of eight separate cables controlled by two 30hp motors. It takes 20 seconds to complete a full transformation.(Hoberman, 2012)

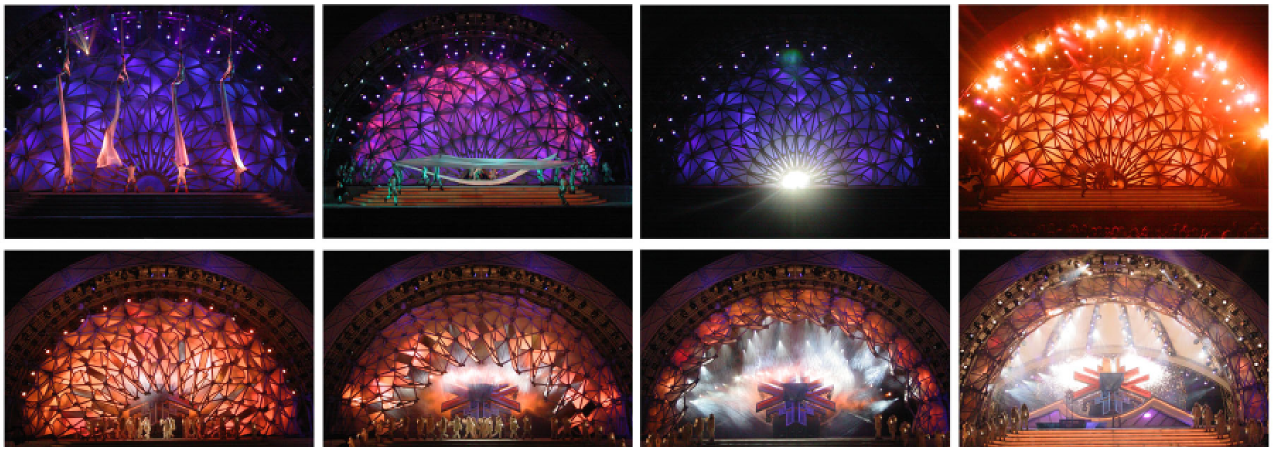


Figure 14 Hoberman Arch, Different Transformations

Observations

This project clearly underlines the complexity involved in making transformable structures into buildings. As of now we see most of the transformable structures are installations where the long term maintenance and durability are not a problem. Nano technology is being heralded as the way to achieve these complex transformations in the future, but there is a long way to go before buildings can be conceived as transformable structures.

Lumenhaus

Location: Independent Installation

Date: 2002-2009

Architect: Multi department collaboration, Virginia Tech

Building Type: Residential

Area: 800 Sqft

Adaptive System: System Intelligence with occupant override capabilities

Figure 15 Lumenhaus

This is a project by Virginia Tech as collaboration between various engineering and Architecture departments of the School. It won the Solar Decathlon Competition in 2010. Though the level of adaptivity is not exceedingly high like a transformable structure, Lumenhaus is projected as a responsive building and claims high energy savings even with minimal levels of adaptivity. The house is inspired by the Farnsworth House, designed by Mies van der Rohe. Lumenhaus is designed as a responsive energy conscious house. There are data capturing systems including sensors inside and a weather station outside. Live data is fed into the computer, and this data is used along with the already available weather data of the site and optimized to set the position of the shutter panels (Figure 16), insulation panels, glass wall and curtain systems, as well as, the pitch of the roof and solar panels. Based on the season these panels move in a single plane

Figure 16 Automated sliding panels

optimizing the energy efficiency in the building In winter, during the day the insulation panels are close on the north side and open on the south side to allow for passive solar heat gain. All shaded screens are left open to maximize daylighting. In the night insulation panels are closed to trap the heat. During Spring day all panles are left open to maximize light and ventilation.The pitch of the roof can also be optimized for energy production or shedding of snow. The owner can choose to override these settings based on his preferences. These preferences are customized to work on mobile devices like iPhone or iPad. There has been mention of the system's ability to take the future changes into the mind and adjust accordingly (Virginia Tech Center,2012).

Observations

Lumenhaus with minimum levels of adaptivity in terms of mechanism adapts well to different weather conditions.. This raises the question, how complex should the adaptive systems be? Should we design systems with higher mechanical complexity or simple systems with higher complexity in terms of intelligence.

Adaptive Fritting

Location: Cambridge, Massachusetts

Date: 2009

Architect: Hobberman Associates

Building Type: School

Adaptive System: Dynamic Façade, System Intelligence Capability

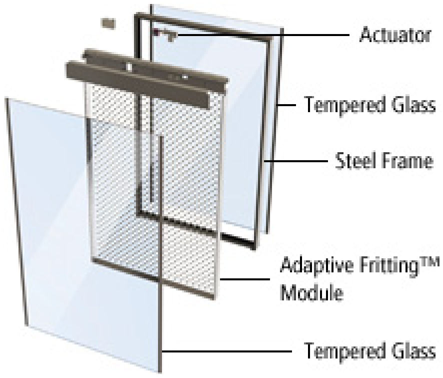


Figure 17 Adaptive Fritting

Adaptive Fritting is an intelligent surface being developed under Adaptive Building Initiative, collaboration between Hoberman Associates and Buro Happold. The system is based on the concept of patterned modules that rotate around a pin thus enabling different levels of Transparency. When the patterns are aligned with each other, it gives maximum transparency and conversely it can become an opaque system. This enables the system to change its transparency dynamically while creating lighting quality sculptive in nature not only in aesthetic point of view but also sustainably efficient.

The Surface can be divided into sub panels. Each panel has a motor which communicates with a centralized processing unit thus enabling control speed of movement of the panels. Any sensor input can also be linked enabling a direct link with any environmental changes like temperature. So we have direct control over shading, solar gain and glare. All the panels can be customized to non-standard free form patterns. Possible applications include facades, roofs, awnings or independent surfaces because of the sculptural quality (Adaptive Building Initiative, 2008).

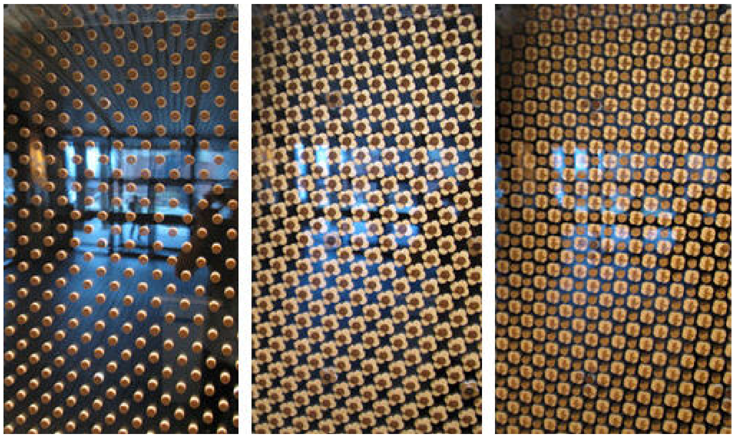


Figure 18 Adaptive Fritting

Observations

Adaptive Fritting has the advantage as independent systems to be fitted into any existing or new setting. This is helped by good customization available, which enables the architect to decide on the shape and pattern to suit specific needs. The other advantage is that, the system behavior can be modified or upgraded in the future to respond to changes with the same adaptive system. In terms of adaptivity, it is similar to Arab Institute, but the system itself is simpler in terms of design and maintenance.

Q1


Figure 19 Adaptive Louvers

Location: Essen, Germany

Date: 2010

Architect: JSWD Architeckten

Climate: Temperate

Building Type: Office

Size: 28,000 Sqm

Adaptive System: Dynamic Façade, System Intelligence with no occupant preference override

The main function of the façade system is to control the entry of light into the building. The shading system is made of 3,150 stainless steel movable vertical fins into which adaptive horizontalstainless steel louvers (Figure 26) are fitted. The wiring for all thse these fins and louvers is housed in the conduits running up and down the façade. the vertical fins rotate 180 degress around the conduits. The horizontal louvers act a mini light shelves and reflect light into the interior spaces. This is an optimized system which takes advantage of both the adaptive horizontal louvers and the adaptive vertical elements.. They move accordingly to the angle of the sun reducing the need for artificial lighting and air-conditioning creating a highly sustainable and energy efficient system. This systems also tries to maximized the views for the users. Apart from the energy efficiency, the façade also defines the character of the building (Grefen , 2010).

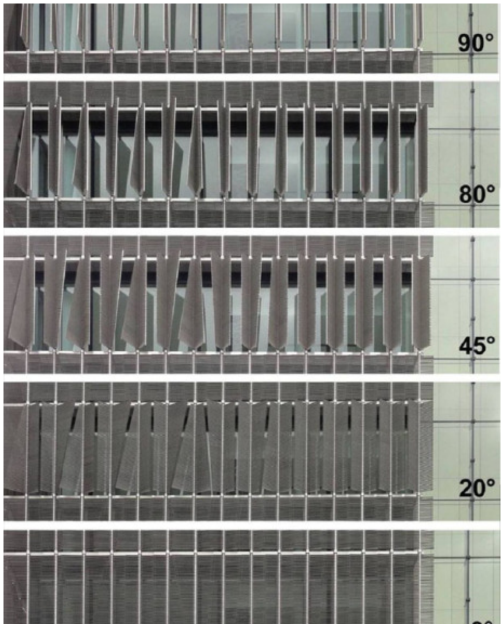


Figure 20 Adaptive Louver Angles

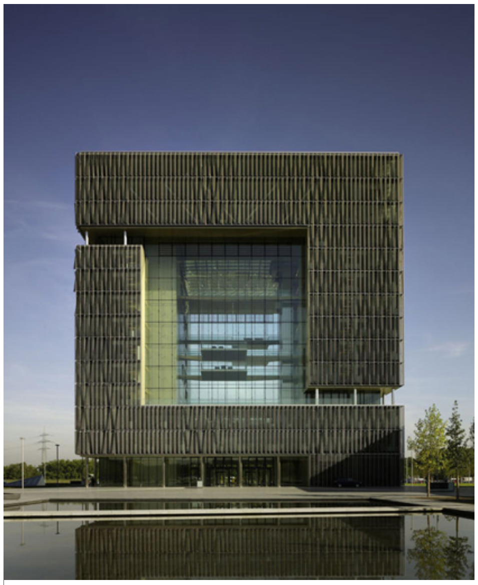


Figure 21 Q1 Facade

Observations

There is no individual user involvement in the system.. The user cannot override any changes made by the centralized system. It is really difficult to incorporate user involvement as the façade is more detached from the interior spaces unlike in GSW.

Homeo Static Façade System

Prototype Stage

Architect: Decker Yeadon

Adaptive System: Dynamic Façade, Smart Materials

Homeostasis is a natural phenomenon where different organisms regulate the internal conditions through different actions. Human sweat is such a response to heat. The homeostasis facade is based on the principle of dielectric elastomers which allows the building façade system to control the solar gains. This system is developed by the research based Architectural practice firm, Decker Yeadon based in New York. The façade regulates internal conditions by responding to external environmental conditions. The elastomer

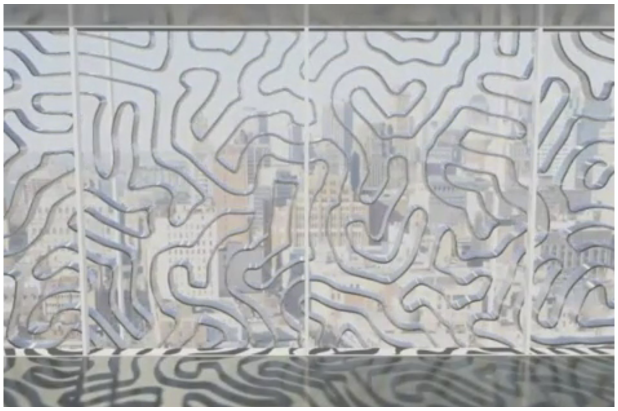


Figure 23 Homeo Static Façade System, fully open

Figure 22 Homeo Static Façade System, partially open

louvers with a silver coating open when illuminated by the sun and close in the absence of the sun. The silver coating produces an electric charge on the surface proportional to the incident light and thus actuates the elastomer. Thus, this system controls the thermal flow thus regulating the internal building temperature. If the temperature is low, the elastomers open allowing in more light and conversely if the temperature is high, elastomers close allowing in lesser light (Minner, 2011).

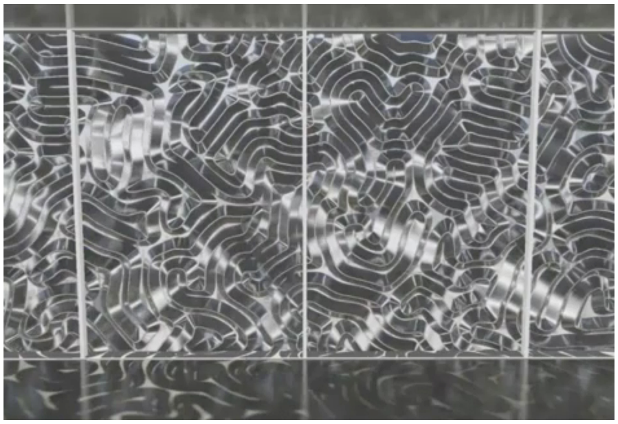


Figure 24 Homeo Static Façade System, closed

Observations

The system is highly responsive even to small changes as it responds in real-time such as to the sun going behind clouds or to the shadows of the neighboring building. As the system does not need any sensors or electrical power to work, it offers exceptional levels of energy efficiency. But this system is very rigid as the user has no control on the system and cannot change according to his mood and need. Also, the system is not controlled by a centralized processing unit; so in the future if necessary it cannot be updated to accommodate changes.

Figure 25 Proposed Smart Screen Rendering

Smart Screen

Prototype Stage

Architect: Decker Yeadon

Adaptive System: Dynamic Façade, Smart Materials

Smart Screen is an Intelligent shading system for facades, based on the principle of thermo responsive smart memory materials that can open and close the perforations in the screen and thus regulate heat transfer through windows. The material used is a nickel titanium shape memory alloy mainly used in medical applications, which changes structure, to pre-determined shapes at specific temperatures. The smart screen is responsive to ambient room temperature and does not require any sensors, motors or electricity as it operates in response to temperature. The smart screen closes to block solar heat gain if the temperature in the space rises and opens the apertures when the space is cooler to allow heat gain. This system is also developed by the research based Architectural practice firm, Decker Yeadon (Decker,2012).

Observations

Similar to the Homeo Static System the Smart Screen is very rigid as the user does not have any role in deciding if the system opens or closes. It has the advantages of being very highly responsive to external conditions as the surface itself is the motor and will work with zero power consumption for the system.

Case Study Conclusions

It can be inferred that the adaptive system behavior itself is more important than the adaptive mechanism. The system behavior can only fulfill the potential of the mechanism. This is analogous to photography saying that a camera body is only as good as the lens. Similarly, we could say that the adaptive mechanism is only as good as its system behavior.

As we have seen in the classification of adaptive systems and the case studies presented above, most of the adaptive systems are dynamic facades. Most of the modern buildings achieve their adaptivity through interpretation of the building skin. The most common form is shading systems which can be blinds, operable louvers or dynamic shading. For this thesis, hypothesized dynamic shading is analyzed, and gains achieved are measured in terms of daylighting performance.

4. Dynamic Shading Systems:

Before getting into the specifications of the shading system and its analysis, it is necessary to look at metrics to be used in the analysis to measure daylighting performance. The metrics used influence the outcome of the analysis.

Existing Day-lighting Metrics:

(Reinhart, Maraljevic and Rogers, 2006)

Daylight factor: This concept is the most outdated and lopsided metric, made entirely keeping a static setting in mind. It is the ratio of illumination between indoors and outdoors under standard overcast skies. It is calculated at the horizontal work plane.

Daylight Autonomy: This concept is the first annualized metric. This enables the possibility of incorporating dynamic shading as it cannot be calculated and optimized for a singular time interval. It is the percentage of annual daytime hours that produce lighting levels above a specified illumination level.

Continuous Daylight Autonomy: Unlike Daylight Autonomy which does not consider the values below the minimum threshold, Continuous Daylight Autonomy gives partial weightage to values below the user defined threshold.

Useful daylight Illuminance: This is a variation of Daylight Autonomy and is based upon three illumination ranges, 0-100 lumen, 100-2000 lumen, and over 2000 lumen. It gives full weightage to values between 100 lumen and 2,000 lumen and partial weightage to the other ranges.

Temporal Daylight Autonomy: This is the fraction of time 75% of the space achieves lighting levels over the specified illuminance threshold.

Spatial daylight Autonomy: This metric report the percentage of sample points in the space that are above the specified minimum daylight illuminance level for a minimum percentage of the time over a year. The target value is usually taken as 50%.

Most of these metrics are quantitative in nature even though they give small idea about the qualitative nature. The most commonly used qualitative aspect is the calculation of glare in a space. In this thesis, this metric is avoided as glare is calculated for a specific view and it is exceedingly difficult when generating values for every 30 min or 1 hour time intervals throughout the year. So instead, the following Qualitative metric is considered to get an idea of the quality of daylight performance.

Coefficient of Variation: The Coefficient of variation of illuminance values of all the sample points in the space gives a good insight into the uniformity of light.

Adopted Metrics:

Useful Nodes: This is the percentage of nodal or sensor points in the spaces analyzed that are between the specified maximum and minimum threshold values. For example, the minimum and maximum threshold values used in the analysis are 200lumen and 2000lumen respectively. This metric is a hybrid of Useful Daylight Illuminance and Spatial Daylight Autonomy

Coefficient of Variation (COV):

The Coefficient of Variation for a space is the standard deviation of the sample points divided by their mean. Higher coefficients mean that there is a greater variation in Daylighting levels and lower coefficients correlate to greater daylighting uniformity. High variation may correlate with glare, so low values are preferred.

Benefit Ratio (Useful Nodes): This is the comparison between useful nodes of two different configurations. In this Analysis, the dynamic configuration is compared to static configuration. Benefit Ratio is the percentage increase in useful nodes.

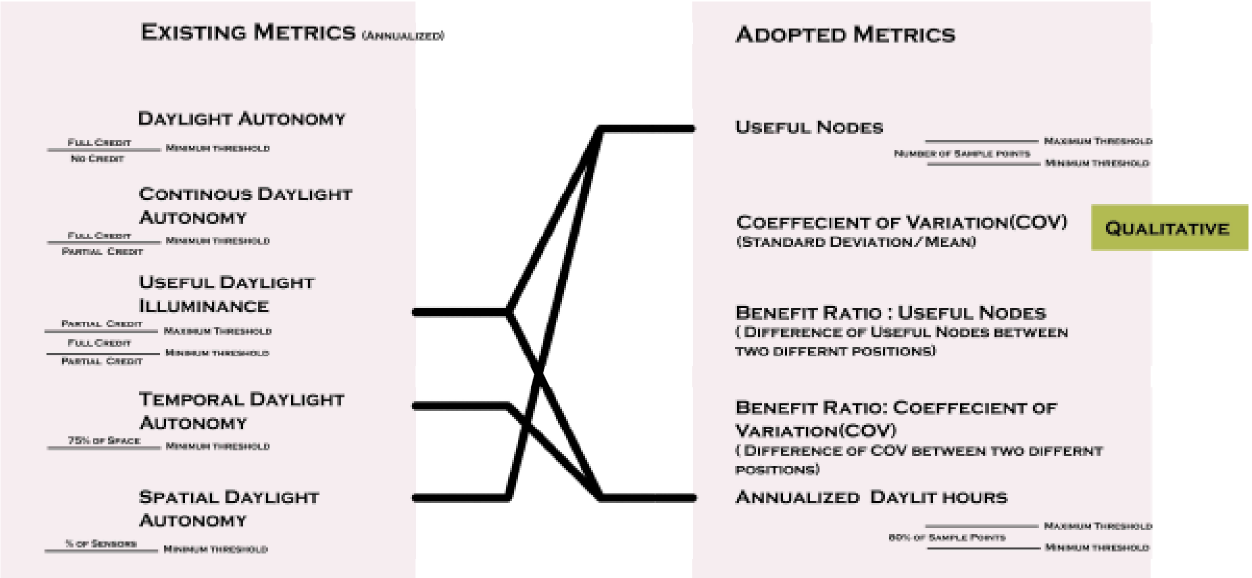


Figure 26 Relation between existing and adopted metrics

UND = Useful Nodes in Dynamic Configuration

UNS = Useful Nodes in Dynamic Configuration

1. BR Useful Nodes = Benefit Ratio (Useful Nodes)

BR Useful Nodes = (UND – UNS)/UNS

Benefit Ratio (COV): This is similar to the above metric except coefficient of variation replaces useful nodes. It is the percentage decrease in the coefficient of variation rather than increase in useful nodes in the previous metric.

COVD = Coefficient of Variation in Dynamic Configuration

COVS = Coefficient of Variation in Static Configuration

BR COV = Benefit Ratio (COV)

BR COV = (COVS – COVD)/COVS

Annualized Daylit Hours (ADH): It is the percentage of hours in a year in which 80% of the total sample points fall between the maximum and minimum threshold Illuminance values considered. Annualized Daylit Hours is a hybrid between Useful Daylight Illuminance and Temporal Daylight Autonomy. For this analysis, the maximum threshold is 2000lumen and the minimum threshold is 200lumen and only the office working hours (8:30am – 5:30pm @ 60min intervals) are counted.

Work Flow

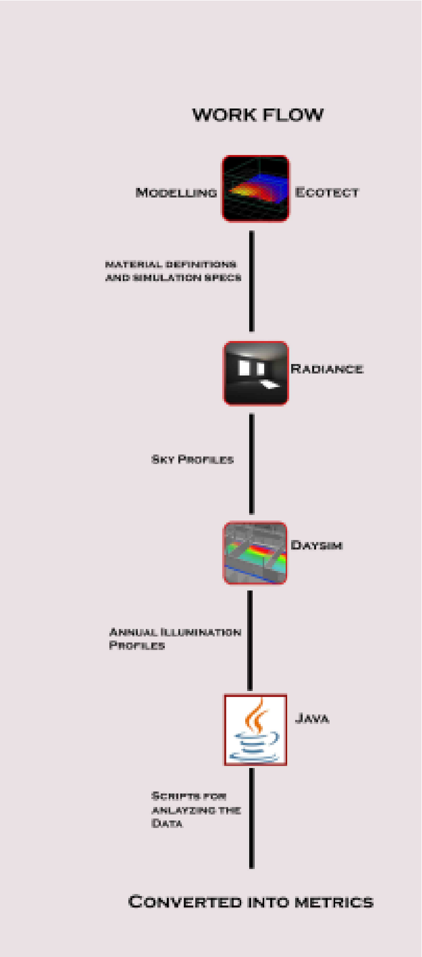


Figure 27 Work Flow

In Ecotect, the basic modeling is done, and material properties are defined. After that in Radiance, material definitions are fine-tuned if necessary, and sky profiles are generated. Using the sky profiles, Daysim generates Annual Illumination Profiles. These profiles have Illuminance values for every sample point for the time interval considered all throughout the year. These values are further processed using custom software, written by the author, to convert them into the metrics adopted for the analysis. Generating the metrics for the dynamic configurations is more complicated. The dynamic configuration is stripped down into individual static positions and analysis is done separately for each of these positions. Afterwards, through scripting these individual results are combined to get the optimized file with the best possible position for every hour throughout the year.

To make the dynamic system more intelligent, thresholds are incorporated while generating optimized files. For example, a threshold of 10 useful nodes is used in the analysis while generating optimized dynamic configurations for useful nodes. At any time interval, the optimized configuration will change only if there is a gain of at least 10 useful nodes. Thus, the system avoids movements with minimal gains and in turn saves energy. Further, the number of position movements in the system annually is tracked. This would also give a good idea about frequency of change of position in the system which will in turn effect the views of the user and energy spent in operating the system.

Future Additions to the Work Flow:

At present, all the metrics are optimized separately. Ideally, all the metrics have to contribute towards one singular optimization. A weighted profile has to be generated to combine Useful Nodes and Coefficient of variation and to optimize them together. Finally, Artificial Intelligence Algorithms might be incorporated to enable the system to become intelligent and flexible to change and adapt over time. A feedback loop should also be enabled to interact and respond to users of the space and understand the patterns of use.

Specifications of Analysis Space

For the analysis, an hypothetical space of 12m X 5m has been considered with south facing window 1300mm high. The sill height is 900mm. Office working hours between 8:30AM and 5:30PM at 60 min intervals are considered for analysis. Also, to study the space in a global perspective, it is analyzed in Quito (Ecuador), Seattle (USA), and Delhi (India) to understand the effect of latitude. The work plane for illumination simulation is 800mm. The work plane is divided into 200 sample points which are used as virtual sensors in the simulation. The following cases are different in the dynamic shading and extent of dynamism being analyzed.

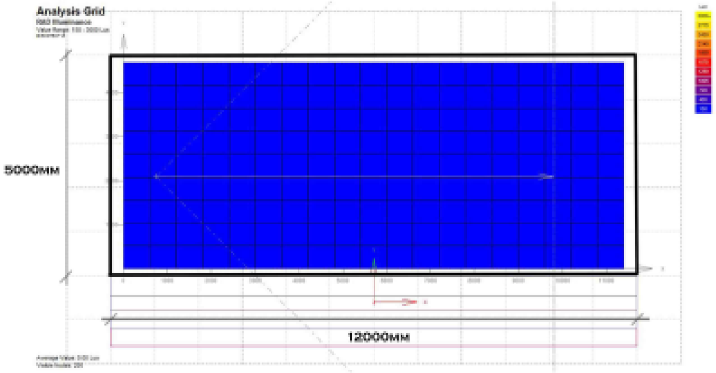


Figure 28 Plan of Simulation Space

Case 800A+E

Static Shading: 800mm depth

Dynamic Shading: The Dynamic Shading will be available to change the depth from 800mm to 1200, 1600, 400, 0 mm. The shading device will be able to change its angle when it is in 800mm position. The possible angles are 30 degree up and down and 60 degree up and down.

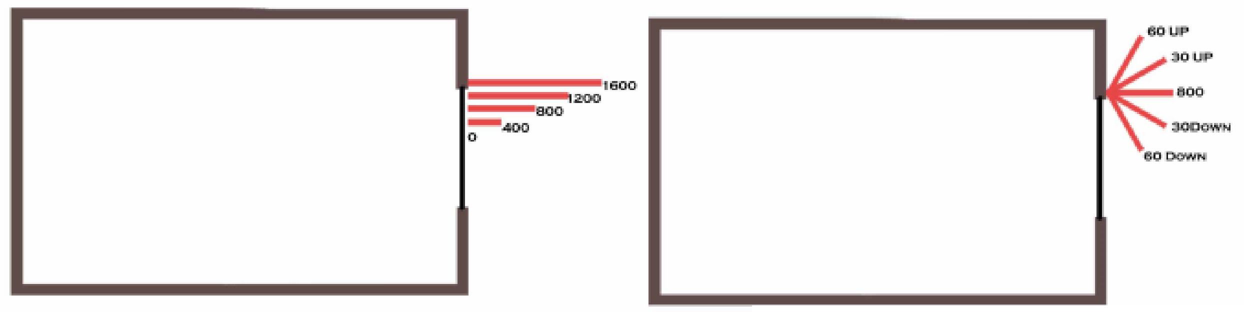


Figure 29 Case 800A+E

Case 800A

Static Shading: 800mm depth

Dynamic Shading: The shading device will be able to change its angle when it is in 800mm position. The possible angles are 30 degrees up and down and 60 degrees up and down.

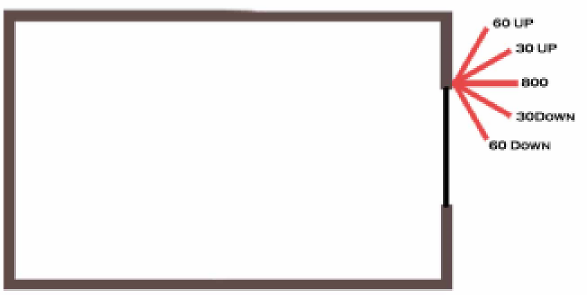


Figure 30 Case 800A

Case 1200A+E

Static Shading: 1200mm depth

Dynamic Shading: The Dynamic Shading will be available to change the depth from 800mm to 1200, 1600, 400, 0 mm. The shading device will be able to change its angle when it is in 1200mm position. The possible angles are 30 degree up and down and 60 degree up and down.

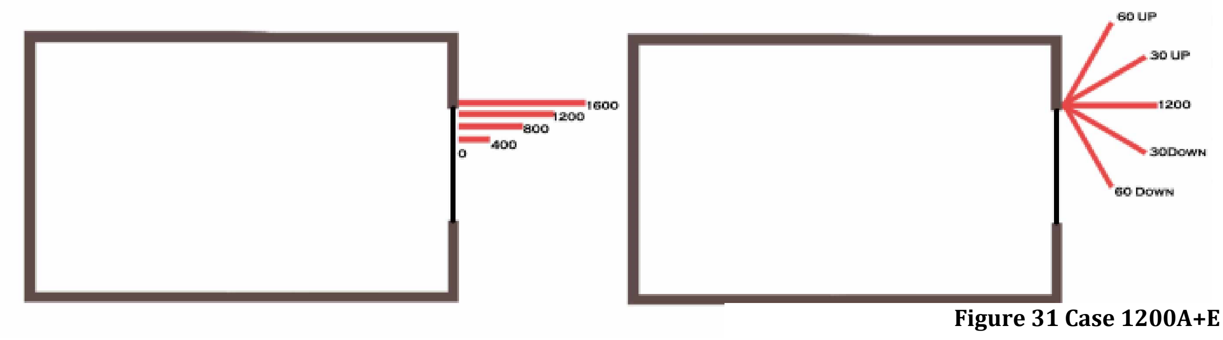


Figure 31 Case 1200A+E

Case 1200A:

Static Shading: 1200mm depth

Dynamic Shading: The shading device will be able to change it angle when it is in 1200mm position. The possible angles are 30 degrees up and down and 60 degrees up and down.

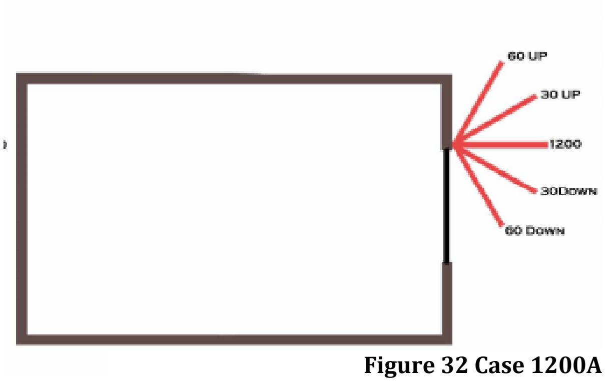


Figure 32 Case 1200A

Case E:

Space Definition: Static Shading: 800mm deep

Dynamic Shading: The Dynamic Shading will be available to change the depth from 800mm to 1200, 1600, 400, 0 mm.

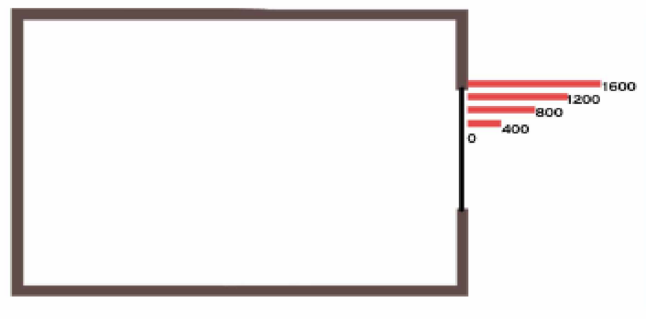


Figure 33 Case E

Initial Results

Case 800+E, Useful Nodes:

Before widespread use of computers for these calculations, only a handful of dates could be compared. Usual practice used the extremes of the solstices and the mid-range equinoxes. I began by examining Delhi using these dates.

Delhi showed significant gains on the winter solstice while the gains were relatively low in the summer solstice and equinoxes. In these graphs, the position changes have also been indicated, which gives an idea about how many times the system adjusts itself in a day. In Seattle, the gains were highly prominent on the equinoxes with lesser gains on the other days. In Quito, the gains are relatively low in all the days considered. Too much emphasis should not be placed on these

Figure 34 Case 800+E Useful Nodes, Delhi

initial readings as the weather data on a specific day can be out of the general pattern. This could result in an anomaly. A similar study has been also done for Coefficient of Variation which gives an initial idea of the difference in a static and a dynamic system

Case 800+E, Coefficient of Variation

Similarly, in Coefficient of Variation the maximum gains are seen in Delhi on the winter solstice with lesser gains on equinoxes. While on the summer solstice, there was no noticeable difference in COV. In Seattle, the maximum gain in COV is seen on the winter solstice while the gains are very low in the other cases. In Quito, there have been no noticeable gains in any of these cases.

Figure 35 Case 800+E COV, Delhi

Final Analysis Results

On the strength of the initial results, I ran the full suite of simulations needed by the optimizer, and then ran the optimizer for each case describe earlier. The important observations from those results are presented here.

Case 800+E, Case 800 A, Case E

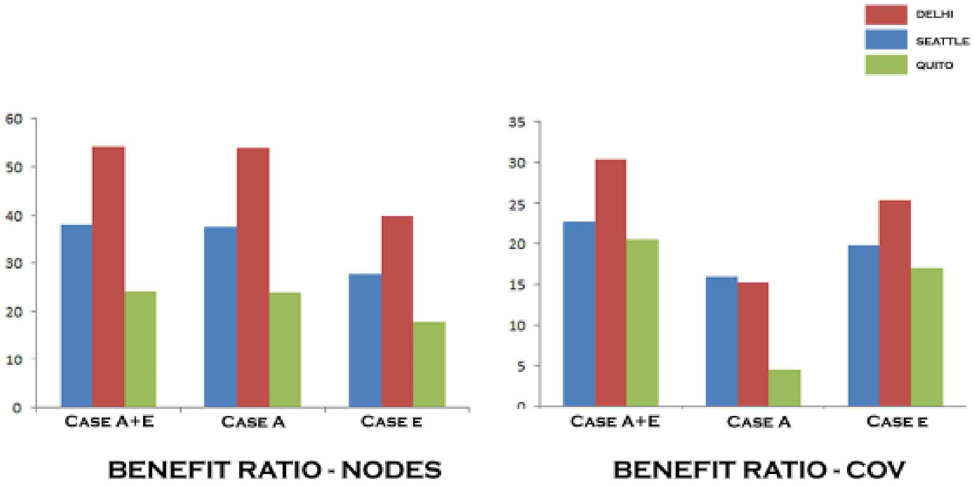


Figure 36 Case 800A+E, Case 800A, Case E: Benefit Ratio Useful Nodes, COV

The benefit ratio for useful nodes was highest in Case800A+E which uses depth adaptivity and angle adaptivity at 800mm depth. Case A which uses only angle adaptivity gets the same gains while depth adaptivity has lesser gains. Delhi has significant gains while Quito has the least with Seattle in between the two. In terms of the coefficient of variation, the combined angle and depth adaptivity have significant gains. Unlike useful nodes, Case A(angle adaptivity) has lesser gains than Case E(Depth Adaptivity). In cities, the maximum gain is in Delhi with Seattle and Quito having lesser gains. In Annual Daylit hours, the maximum hours are gained in Delhi with Seattle and

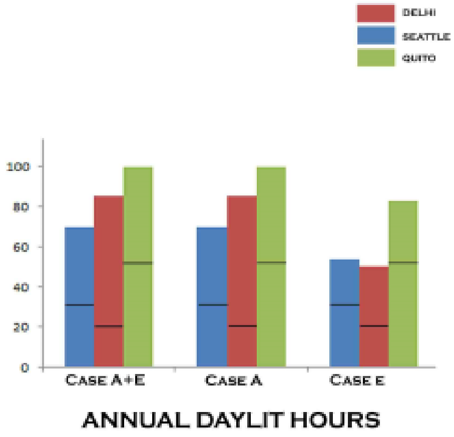


Figure 37 Case800+E, Case 800A, Case E : Annual Daylit Hours

Quito have similar but lesser improvements. The figure shows the daylit hours in optimized dynamic positions while the markings indicate the static daylit hours.

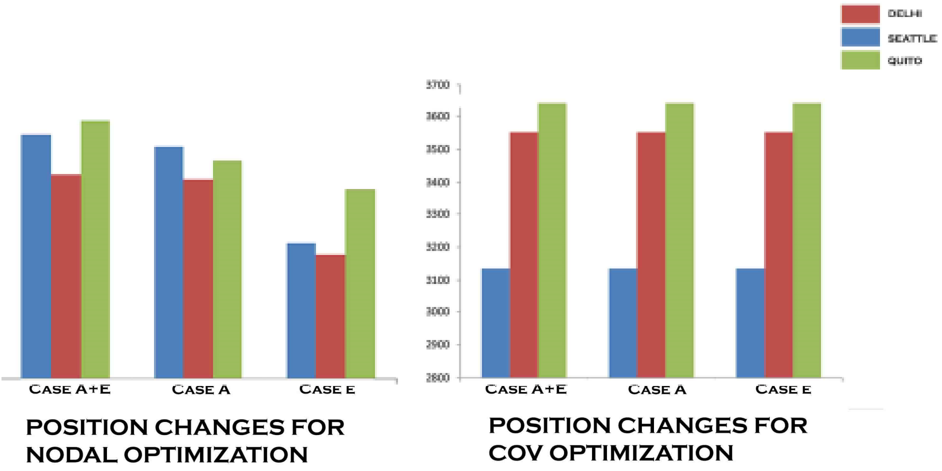
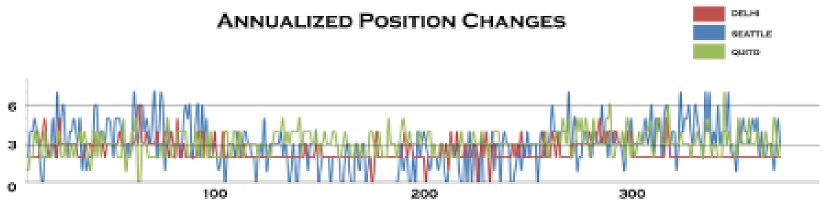


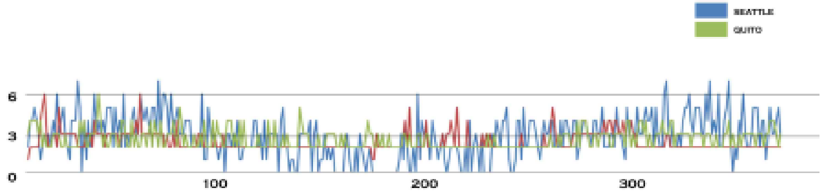
Figure 38 Case800A+E, Case 800A, Case E : Position Changes

The figure shows the number of position changes for each metric for optimization. In Nodal optimization of Case E (depth adaptivity), the number of changes is the least. In the COV optimization, the number of changes for Seattle is much less compared to Delhi and Quito.

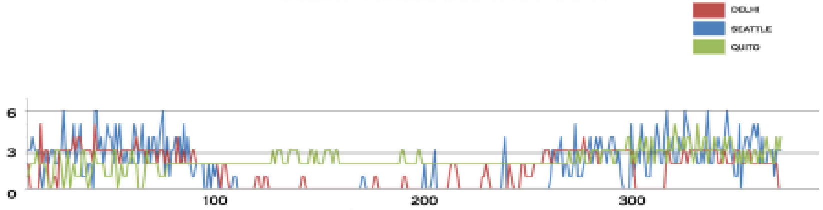
The figure shows the annualized number of changes in a day for nodal optimization. The general number of changes in a day vary from 0 to 7.



CASE A + E ANGLE & DEPTH ADAPTIVITY

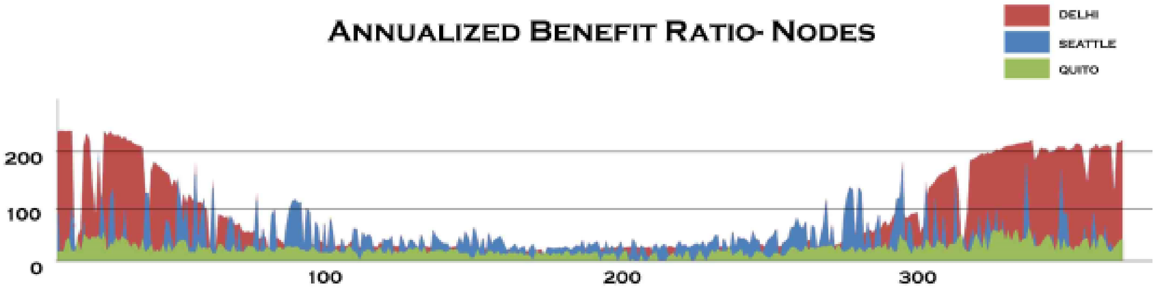


CASE A - ANGLE ADAPTIVITY @ 800

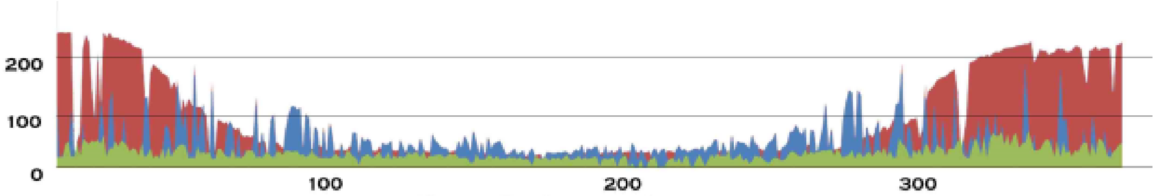


CASE E - DEPTH ADAPTIVITY

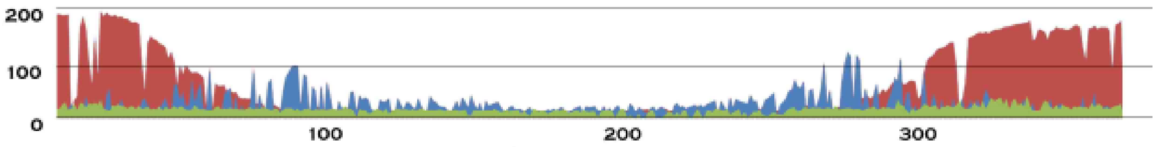
Figure 39 Case800A+E, Case 800A, Case E: Annualized Position Changes for Nodal Optimization



CASE A + E ANGLE & DEPTH ADAPTIVITY



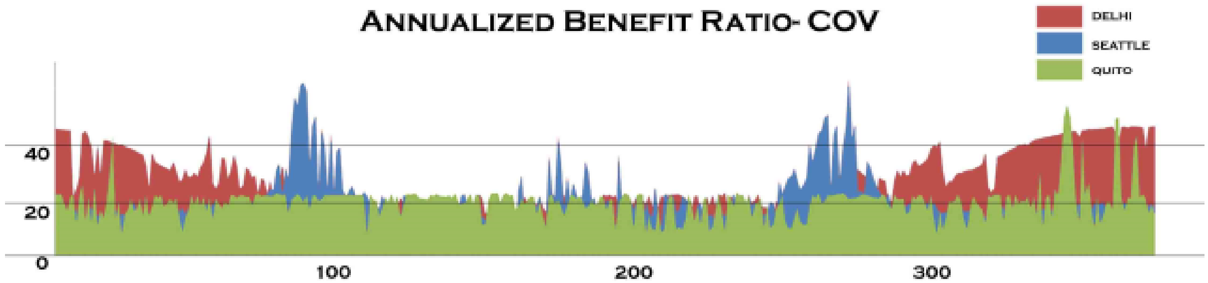
CASE A - ANGLE ADAPTIVITY



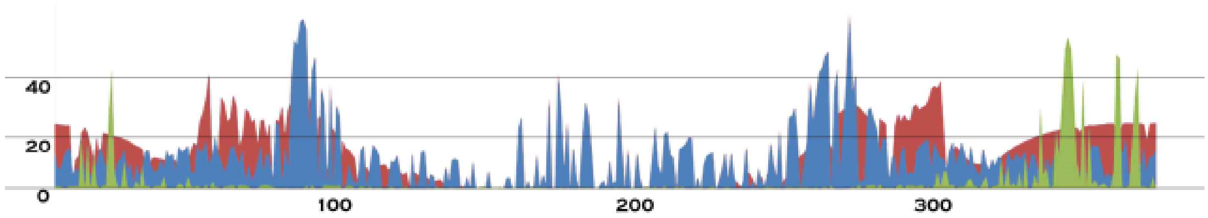
CASE E - DEPTH ADAPTIVITY

Figure 40 Case800A+E, Case 800A, CaseE : Annualized Benefit Ratio: Useful Nodes

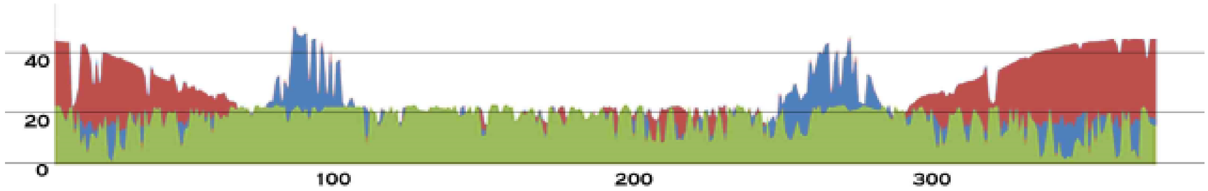
This figure shows the annualized benefit ratio for useful nodes and COV. In terms of useful nodes, in Delhi clearly the maximum benefit is in the winter months with minimal gains in the summer. While Quito has a constant and extremely minimal gain all throughout the year, gains in Seattle are extremely erratic without following a pattern. In terms of COV, there is a similar trajectory in Delhi to useful nodes scenario. In Quito, the gains are more pronounced than useful nodes except for Case A, which has very minimal gains. These results match with the initial analysis results. In Seattle, the benefits are more pronounced around the equinoxes.



CASE A + E ANGLE & DEPTH ADAPTIVITY



CASE A - ANGLE ADAPTIVITY



CASE E - DEPTH ADAPTIVITY

Figure 41 Case 800A+E Case 800A Case E : Annualized Benefit Ratio: COV

Final Analysis Results CASE 1200A+E, Case 1200A, Case E :

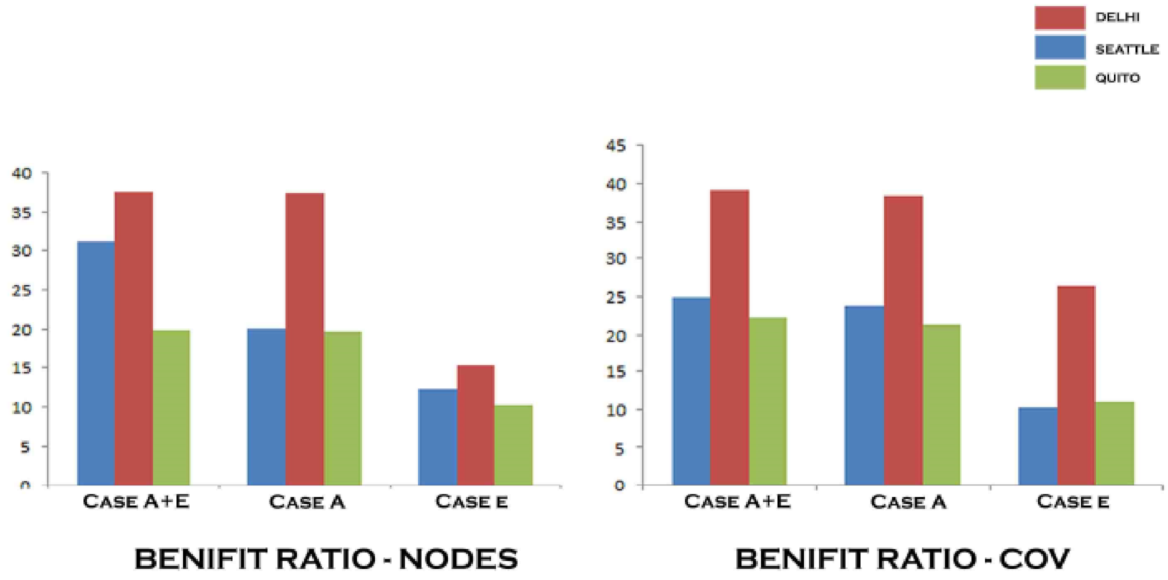


Figure 42 Case 1200A+E, Case 1200A, CaseE : Benefit Ratio

In this scenario, when the dynamic configuration is compared to a static configuration of depth 1200mm the benefit ratios for both Nodes and COV are less when compared to the previous scenario(Case 800A+E). Similarly, the benefit in annual daylit hours is also less. But the general patterns in both the scenarios (Case 1200A+E, Case 800A+E) remain similar.

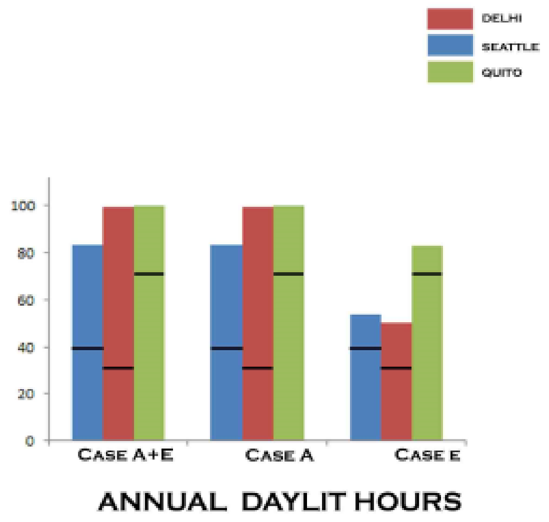


Figure 43 Case 1200A+E, Case 1200A, Case E: Annual Daylit

5. Conclusions & Future Directions:

The principle motivation behind this thesis was to encourage the consideration of Dynamic Shading systems as an alternative to traditional static systems. As of now the adaptive systems are not even considered in the design development process. Through the promising results, it is clear that depending on the scale, site and context of the project it could be a good option. From the analysis until now, it could be said that dynamic shading is a highly sustainable solution in Delhi. Even Seattle has decent gains, but in Quito the gains are comparatively lesser. As a result, dynamic shading may not be the most sustainable option even though it improves the qualitative nature of light.

Increase in Annual Daylit Hours(Case 800A+E)(relative to a static system) :

Delhi 305%; Seattle 105%; Quito 75%.

This thesis also raises many intriguing questions which could provide future directions for research. The number of position changes for the dynamic shading varies from 1 to 4 per day (broadly if the extremities are eliminated). This raises the possibility that the changes can be done manually instead of through an automated system. This would have a enormous impact on the cost of the system. If the results and changes of the system are generalized for times with maximum benefits, mechanical dynamic shading could be a viable option. This is an area that could be researched further.

Discussions at the jury have also raised some compelling questions and directions. What is the performance similarity or difference for cities falling on the same latitude? Does the latitude relation in terms of analysis results correlate to other cities? It would be interesting to look at the performance in terms of existing metrics qualitatively and quantitatively.

Future directions will also include the study of other dynamic shading systems commonly used, including blinds and louvers. Other systems enabled with smart materials such as electro-chromic materials would also be studied further. Other systems like adaptive light shelves could also be interesting to study further.

The development of the scripts and the work flow was generalized so that it could be adapted to any dynamic system. In a way, a tool-like quality allows to study and analyze different systems and process and generate lots of information automatically. If the work flow can be improved to incorporate some of other dynamic factors like user patterns, ventilation, insolation etc.; It also opens up the future possibility of converting the scripts into a plugin for a software.

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Appendix

a) Source Code:

The custom scripts, simulation files and detailed analysis results can be accessed through the following link.

http://dmg.be.washington.edu/projects/DSA/

b)Analysis Results:

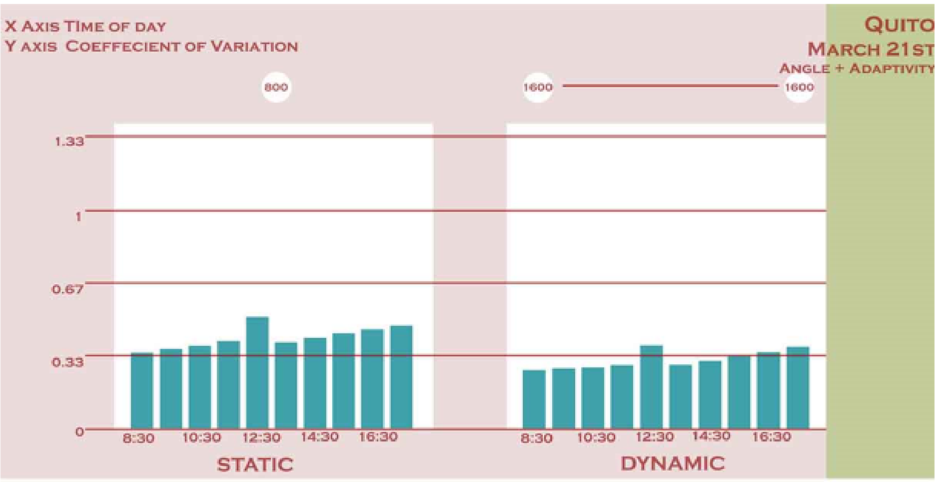
Fig A.1: Initial Results: Useful Nodes with Position Changes, Delhi, Case 800A + E

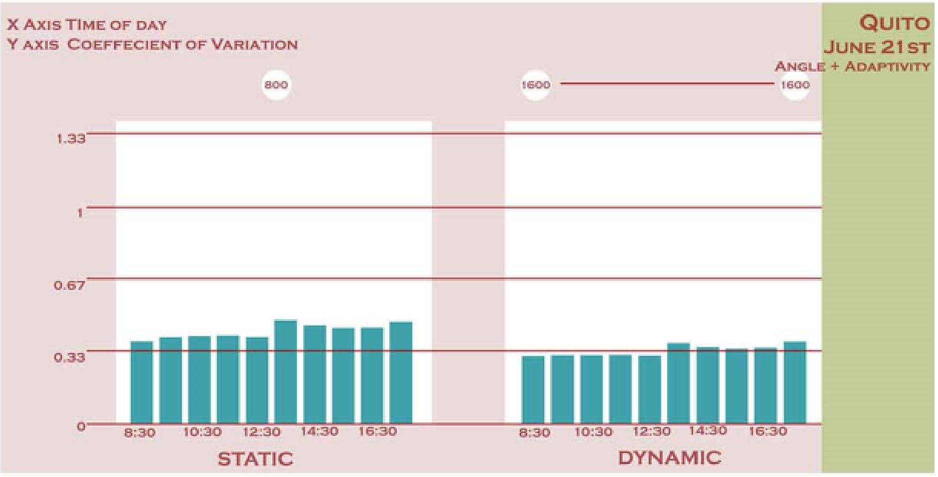
Fig A.2: Initial Results: Useful Nodes with Position Changes, Seattle, Case 800A + E

Fig A.3: Initial Results: Useful Nodes with Position Changes, Quito, Case 800A + E

Fig A.4: Initial Results: COV with Position Changes, Delhi, Case 800A + E

Fig A.5: Initial Results: COV with Position Changes, Seattle, Case 800A + E





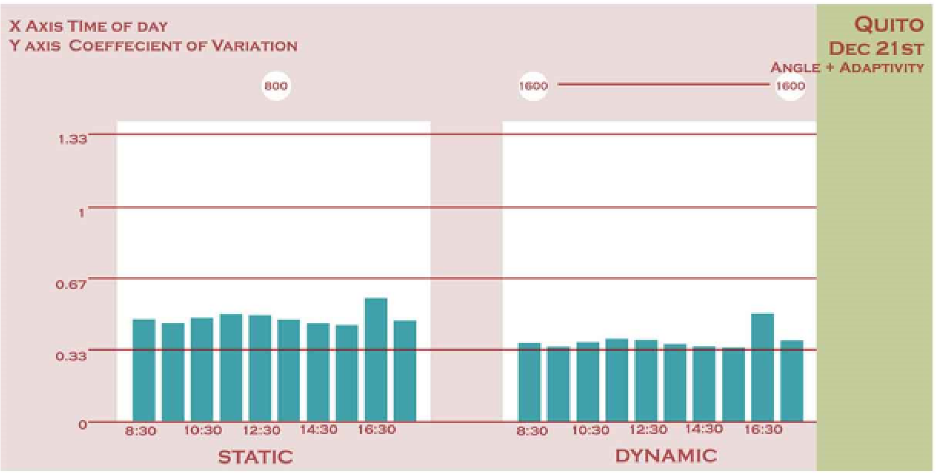


Fig A.6: Initial Results: COV with Position Changes, Quito, Case 800A + E

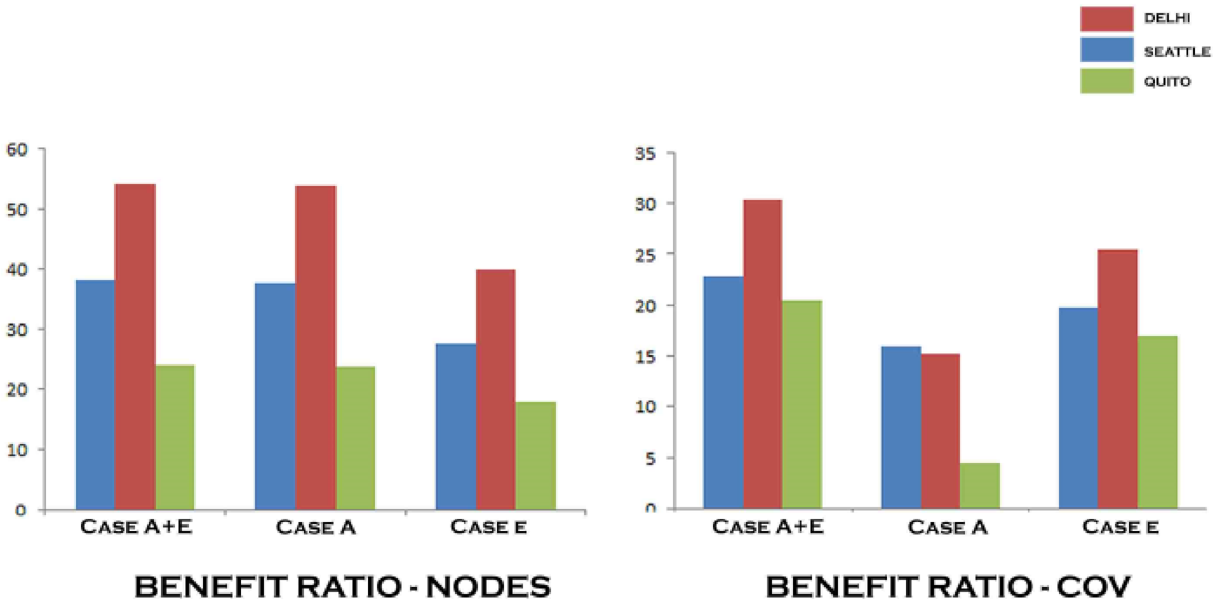


Fig A.7: Final Results: Benefit Ratio, Useful Nodes: Case 800A +E, Case 800 A, Case E

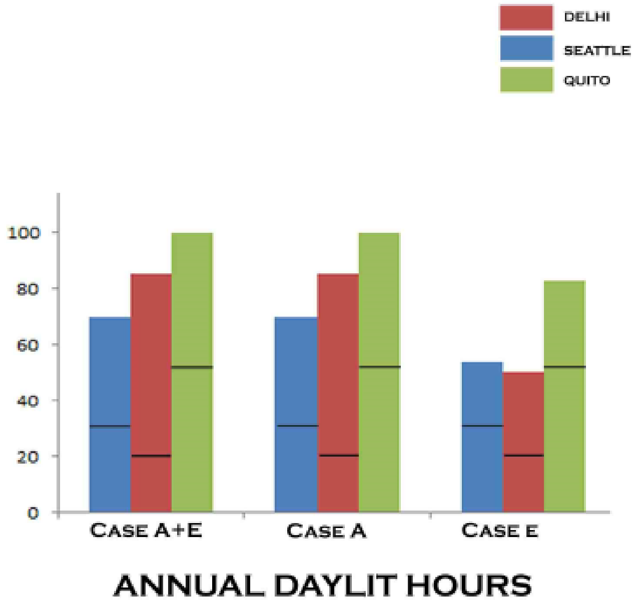


Fig A.8: Final Results: Annual Daylit Hours: Case 800A +E, Case 800 A, Case E compared to a 1200 Deep Static System(The Horizontal lines indicate the Annual Daylit hours of a Static System)

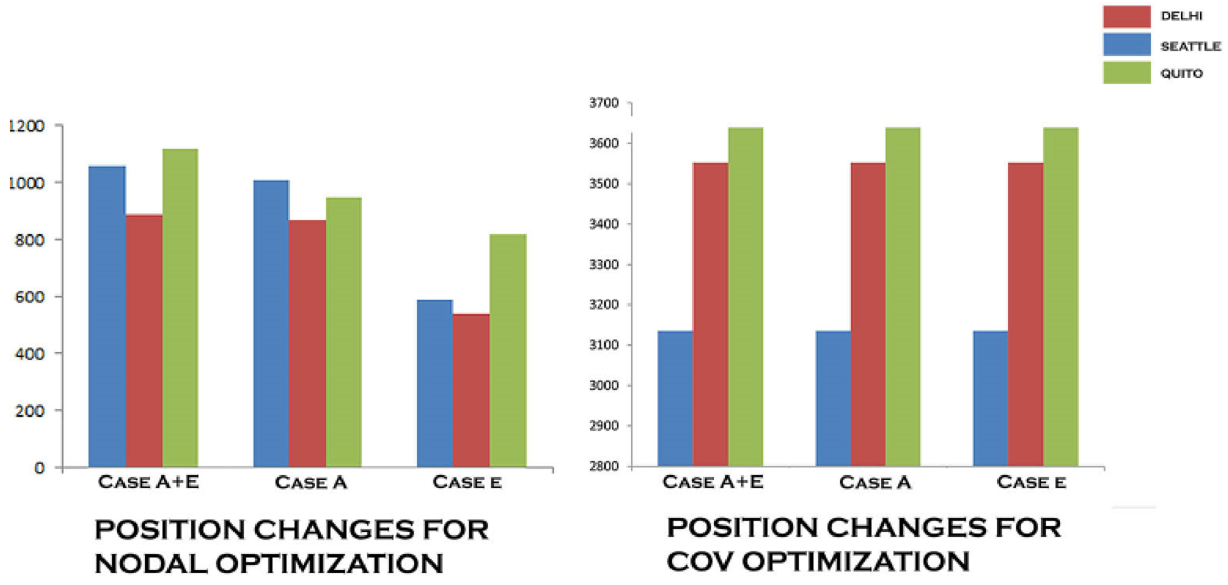


Fig A.9: Final Results: Position Changes: Case 800A +E, Case 800 A, Case E

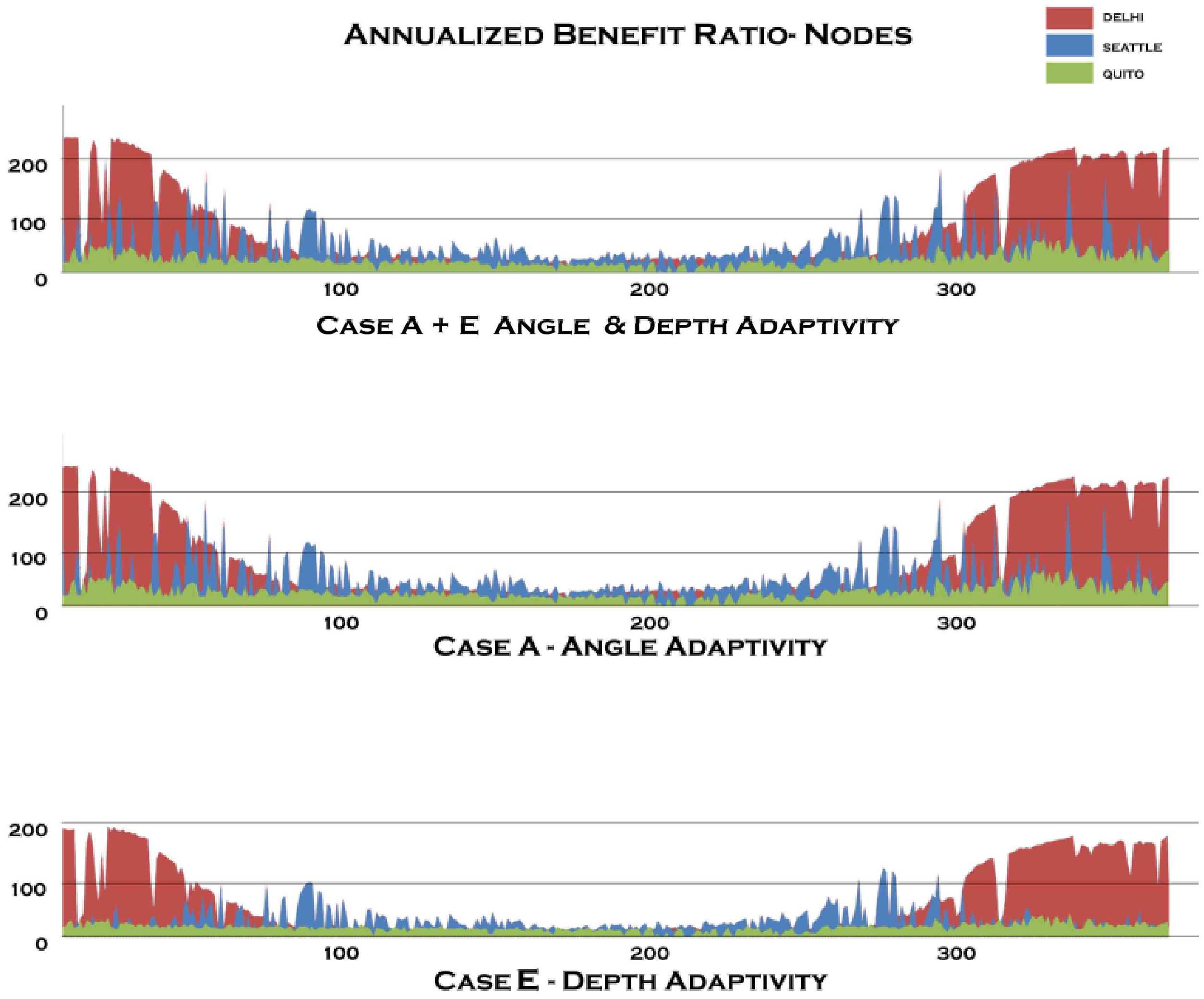


Fig A.10: Final Results: Annualized Benefit Ratio, Useful Nodes: Case 800A +E, Case 800 A, Case E

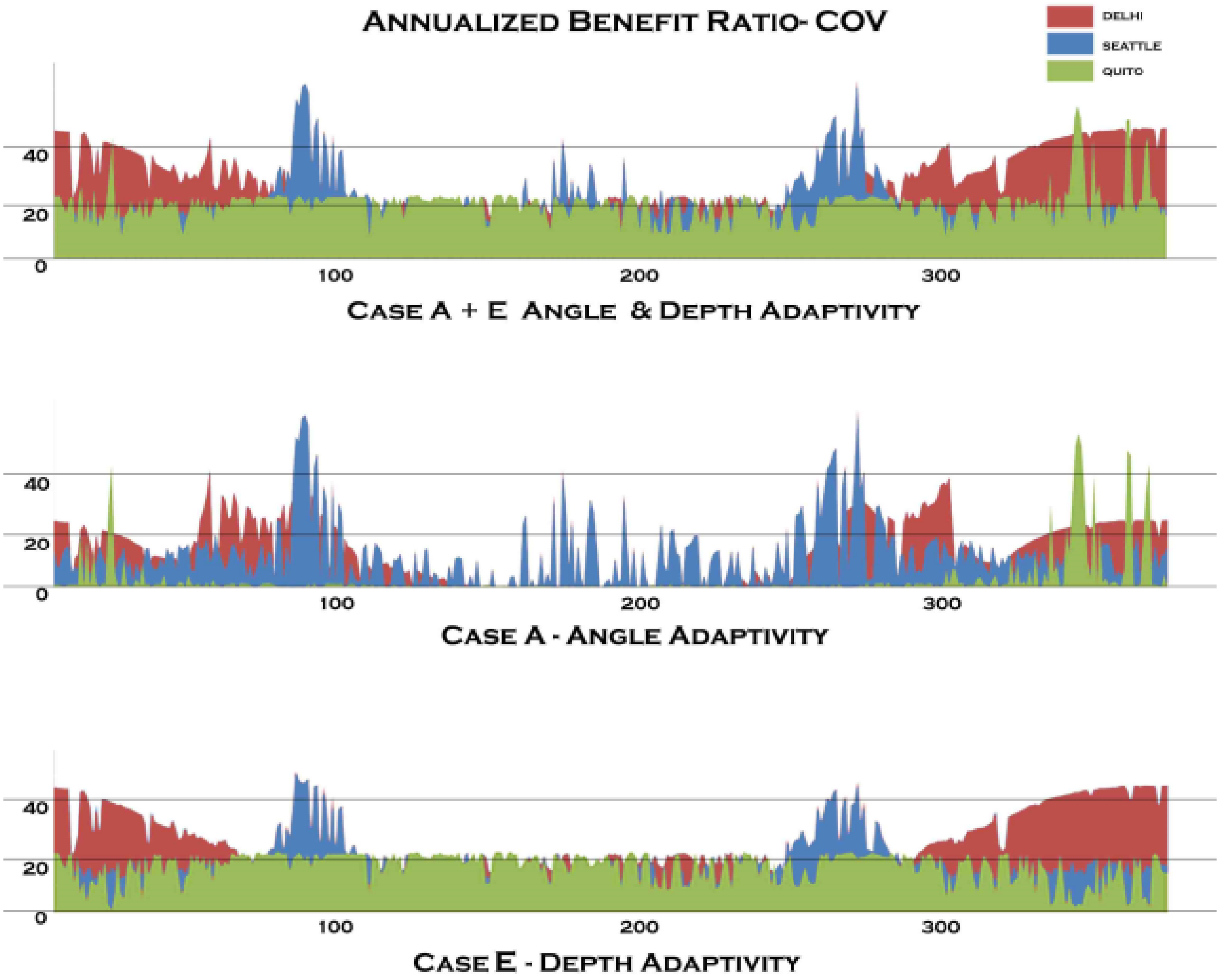
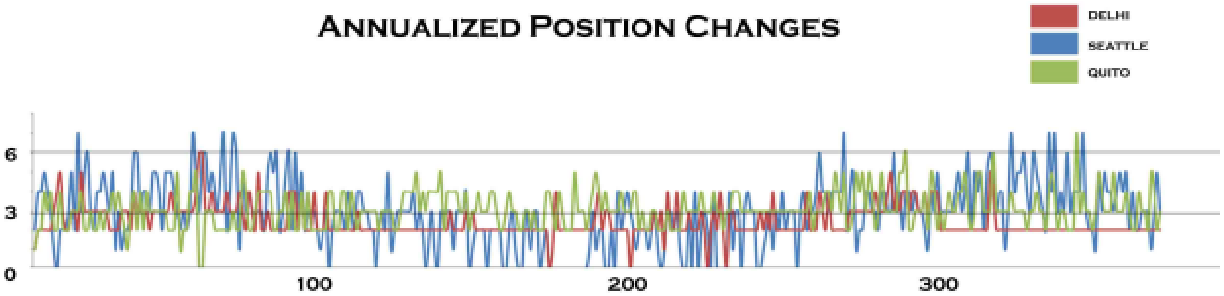
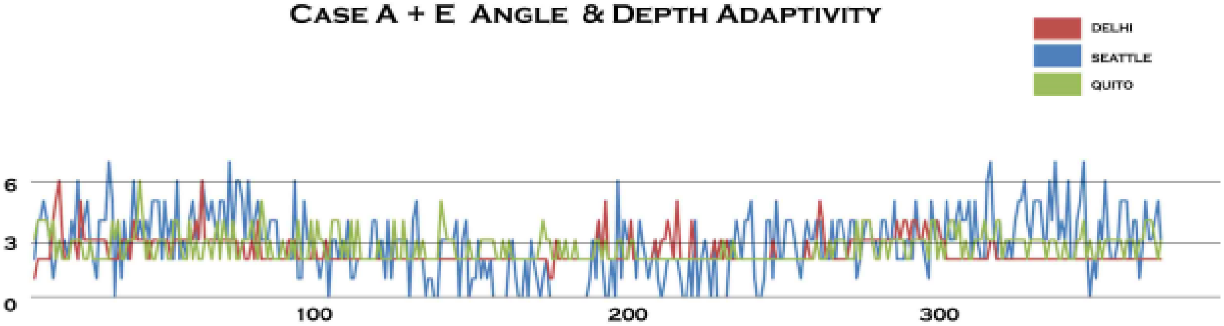


Fig A.11: Final Results: Annualized Benefit Ratio COV: Case 800A +E, Case 800 A, Case E

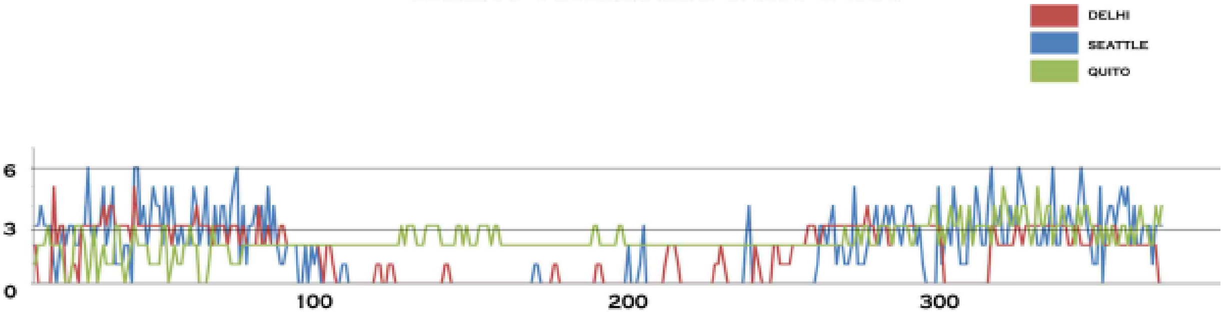
ANNUALIZED POSITION CHANGES



CASE A + E ANGLE & DEPTH ADAPTIVITY



CASE A - ANGLE ADAPTIVITY @ 800



CASE E - DEPTH ADAPTIVITY

Fig A.12: Final Results: Annualized Position Changes for Nodal Optimization:

Case 800A +E, Case 800 A, Case E

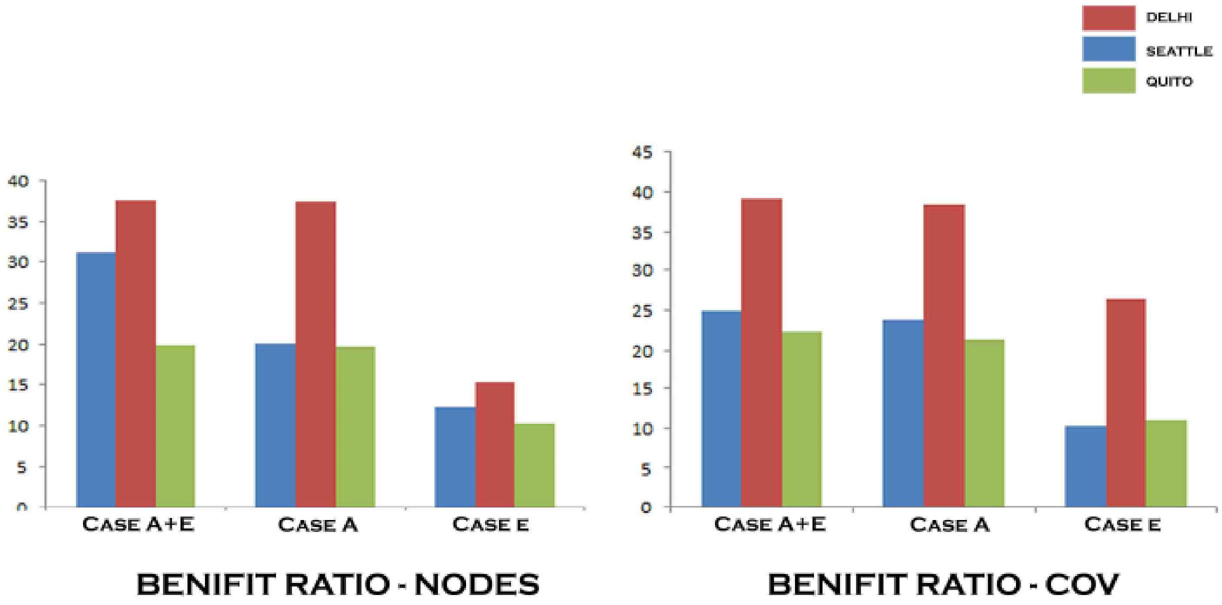


Fig A.13: Final Results: Benefit Ratio: Case 1200A +E, Case 1200 A, Case E

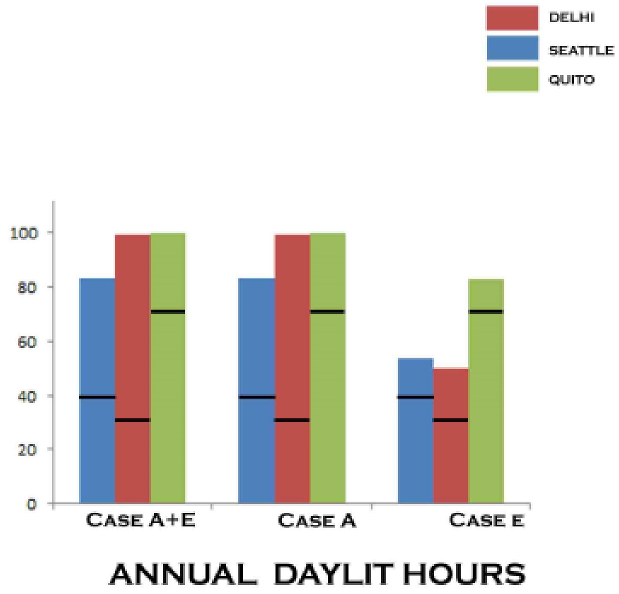
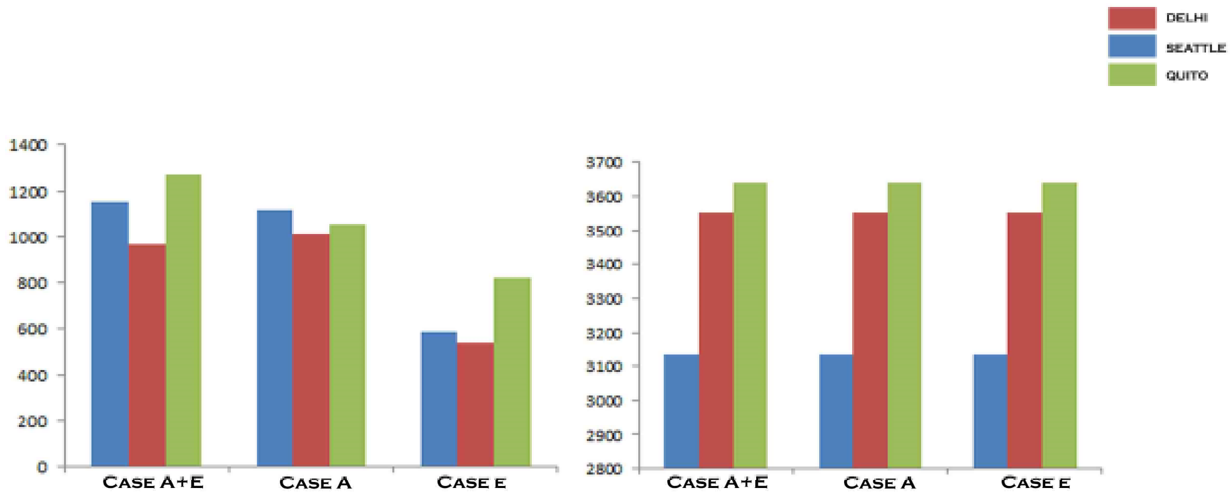


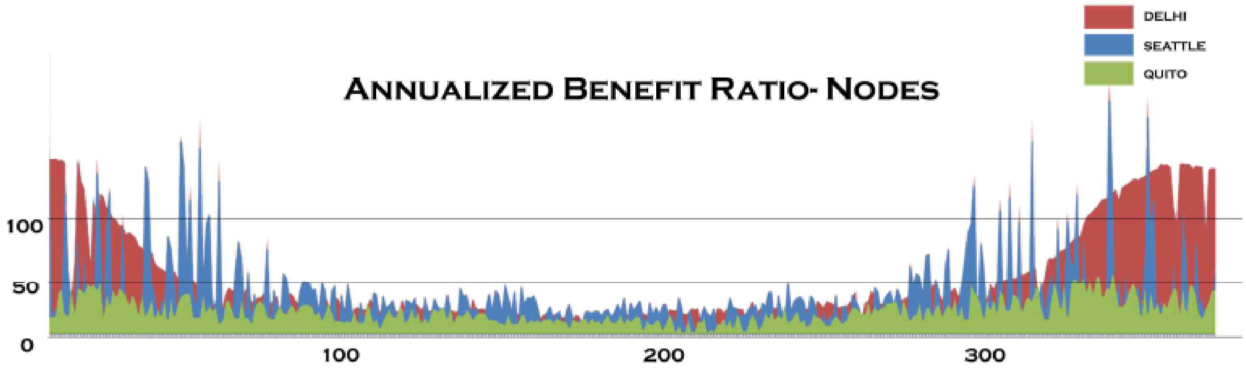
Fig A.14: Final Results: Annual Daylit Hours: Case 1200A +E, Case 1200 A, Case E compared to a 1200 Deep Static System(The Horizontal lines indicate the Annual Daylit hours of a Static System)



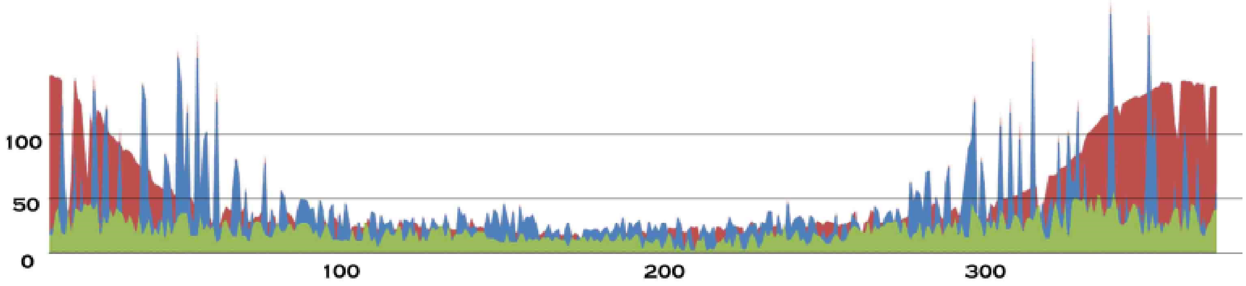
POSITION CHANGES FOR NODAL OPTIMIZATION

POSITION CHANGES FOR COV OPTIMIZATION

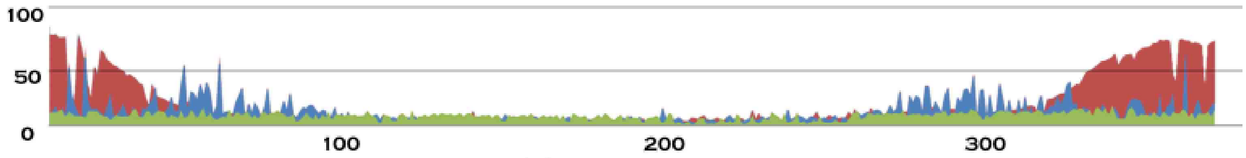
Fig A.15: Final Results: Position Changes in a Year: Case 1200A +E, Case 1200 A, Case E



CASE A + E ANGLE & DEPTH ADAPTIVITY



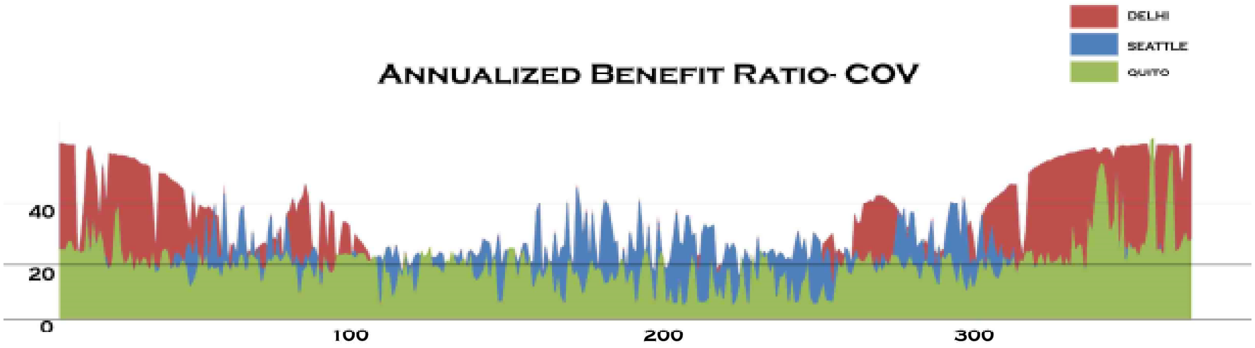
CASE A - ANGLE ADAPTIVITY



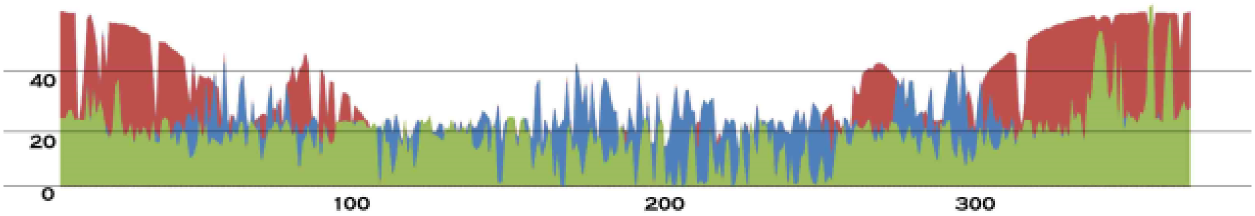
CASE E - DEPTH ADAPTIVITY

Fig A.16: Final Results: Annualized Benefit Ratio, Useful Nodes: Case 1200A +E, Case 1200A, Case E

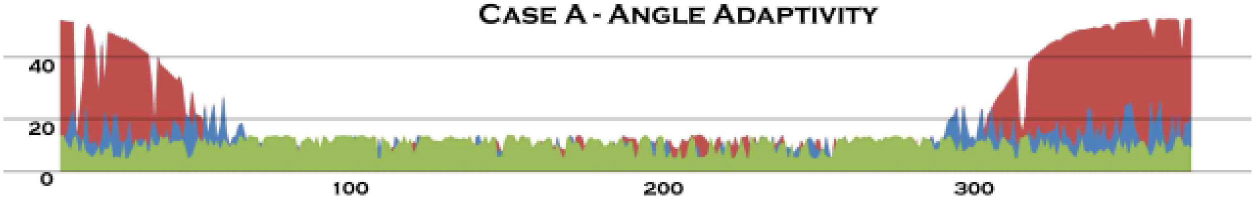
ANNUALIZED BENEFIT RATIO- COV



CASE A + E ANGLE & DEPTH ADAPTIVITY



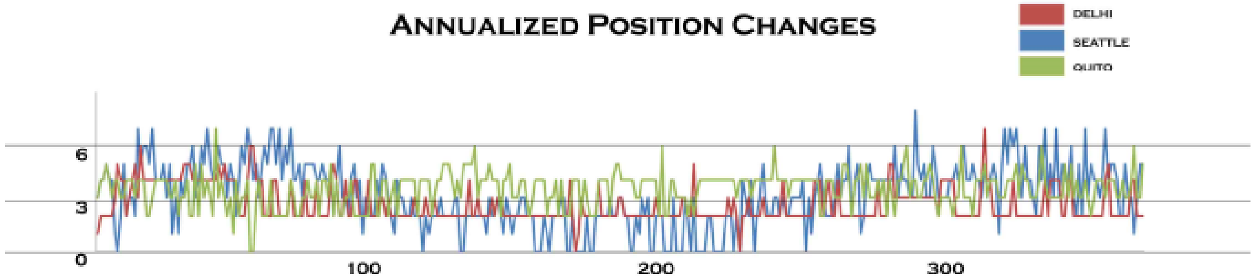
CASE A - ANGLE ADAPTIVITY



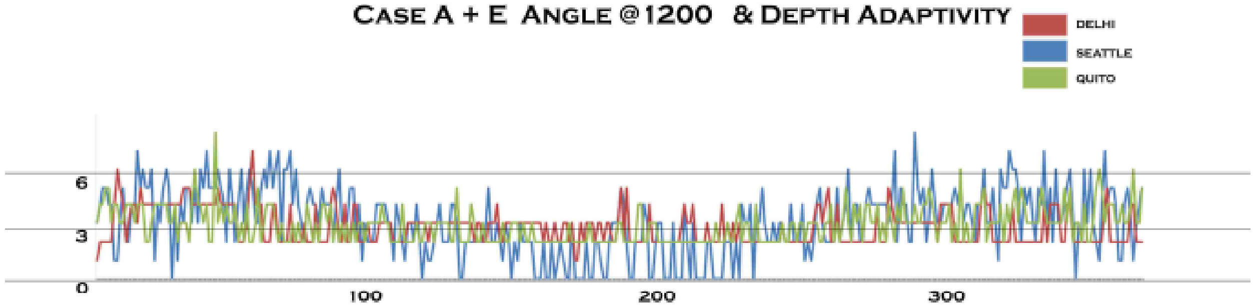
CASE E - DEPTH ADAPTIVITY

Fig A.16: Final Results: Annualized Benefit Ratio, COV: Case 1200A +E, Case 1200A, Case E

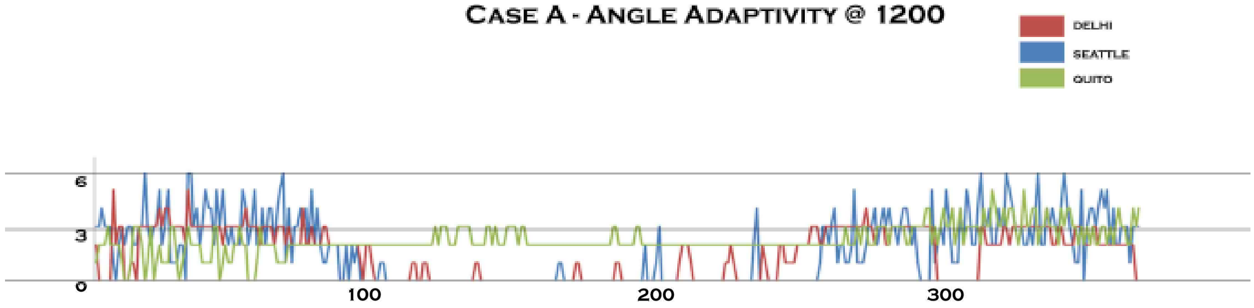
ANNUALIZED POSITION CHANGES



CASE A + E ANGLE @1200 & DEPTH ADAPTIVITY



CASE A - ANGLE ADAPTIVITY @ 1200



CASE E - DEPTH ADAPTIVITY

Fig A.17: Final Results: Annualized Position Changes for Nodal Optimization: Case 1200A +E, Case 1200 A, Case E