ADAPTIVE SYSTEMS FOR OPTIMIZATION OF DAYLIGHTING

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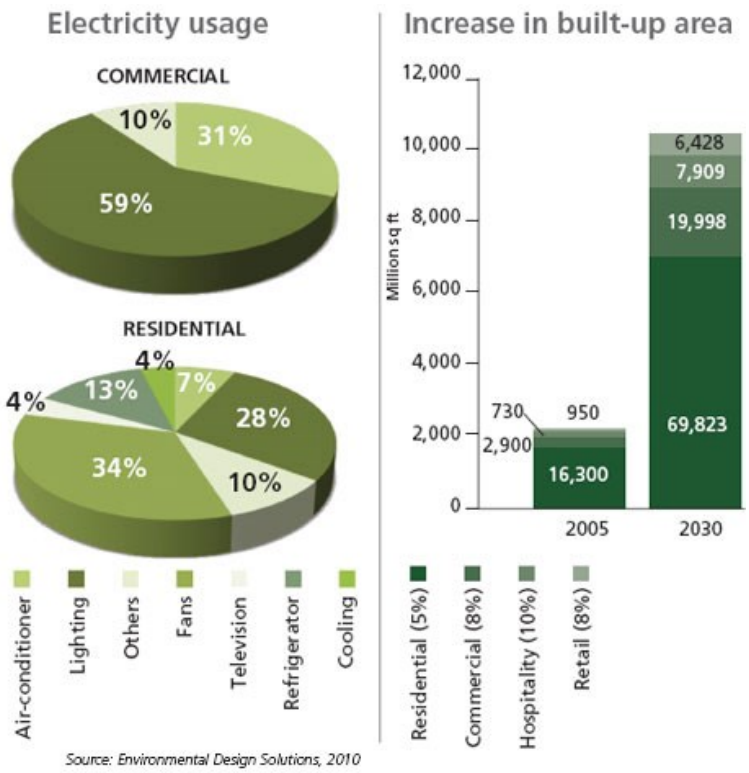
Abstract

Buildings consume more than one third of the country's total electricity. According to the National Habitat Standard Mission, building energy consumption has increased from 14% in 1970 to 33% 2004-05 (Chowdhury, 2012). In Commercial buildings, the primary contributor to electricity consumption has been artificial lighting. Thus, substantial deduction in energy consumption of buildings can be achieved by optimizing daylighting in commercial buildings by reducing the use of artificial lighting (Lee & Selkowitz, 2006). However, because the availability of natural light changes dynamically; the design of static systems adhering to both high and low levels of daylight is difficult. This research hypothesizes a adaptive system and analyses the benefits for optimizing a space for daylighting. This research will also explore how the benefits of this hypothesized system changes with respect to location (latitude).



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1. Introduction:

Aim:

The aim of this research is to compare adaptive shading with traditional fixed shading(the fixed shading base case will be different for each specific adaptive system) to analyze and infer the gains in daylighting quantitatively and qualitatively with specific to geographical location.

Research Questions:

- What benefits of adaptive shading when compared to the traditional fixed shading in terms of daylighting in both qualitative and quantitative aspects?
- How does the geographical location (altitude) affect the benefits of an adaptive shading when compared to fixed shading?

Objectives:

To understand existing research in adaptive systems and classify different types of adaptive shading.

To identify adaptive shading elemental in nature to adopt for research.

To Optimize these various adaptive system and analyze the benefits in comparison to a fixed shading both quantitatively and qualitatively

To understand how these adaptive systems work in different geographic locations

To adopt a metric that is appropriate to the dynamic nature of adaptive system

Scope and Limitations:

The Adaptive system adopted is a hypothetical system with the ability to kinetically move. As it is a hypothetical system there are some liberties taken in its functionality. Even though the adaptive systems are categorized into different types and then and chosen type further into different systems; these categorization still wouldn't cover the whole breadth of adaptivity possible. Normally good adaptive systems have manual override capabilities which are not considered for the adaptive shading systems hypothesized.

All the internal factor factors are generalized and the external factors like obstructions from other buildings are not taken into consideration. The maximum efficiency of the adaptive system can be achieved only in tandem with a suitable artificial lighting system; in this research only daylighting levels excluding the artificial lighting system are accounted in the simulations done. In this study, the shading system is considered on the south side. The layout of the space selected will try to emulate the typical layout in an office. Different geographical locations (latitude) are identified for this study which includes Delhi, Quito and Seattle.

2. Research Methodology:

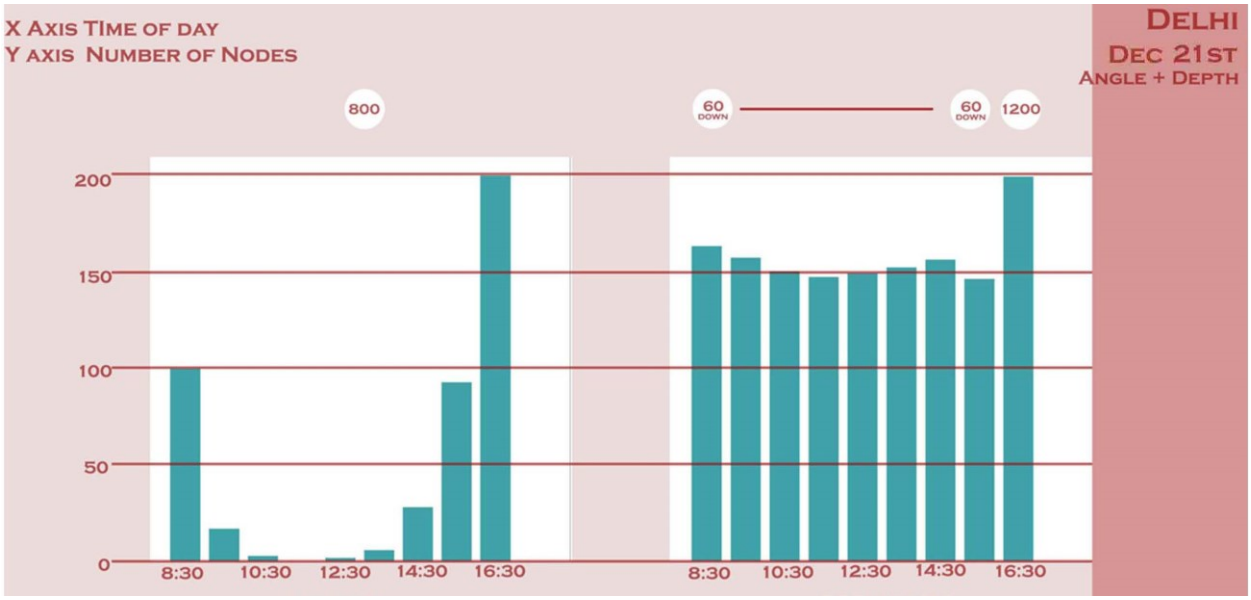

Fig.2: Comparison between static and adaptive System done during the research

Type of Research: Explanatory and Empirical

Type of Research: Experimental, Explanatoryand Empirical

The research idea will be explored through literature review by going through the existing research and categorizing the existing types of adaptive shading. From this classification, specific type of adaptive shading will be selected for the research which is elemental in nature. A similar analysis space will be used for all the systems and an appropriate metric to measure the illumination profiles will be adopted and used for all the different cases . Different systems pertaining to the elemental type of adaptive shading will be selected and the following process will be done for each of the systems.

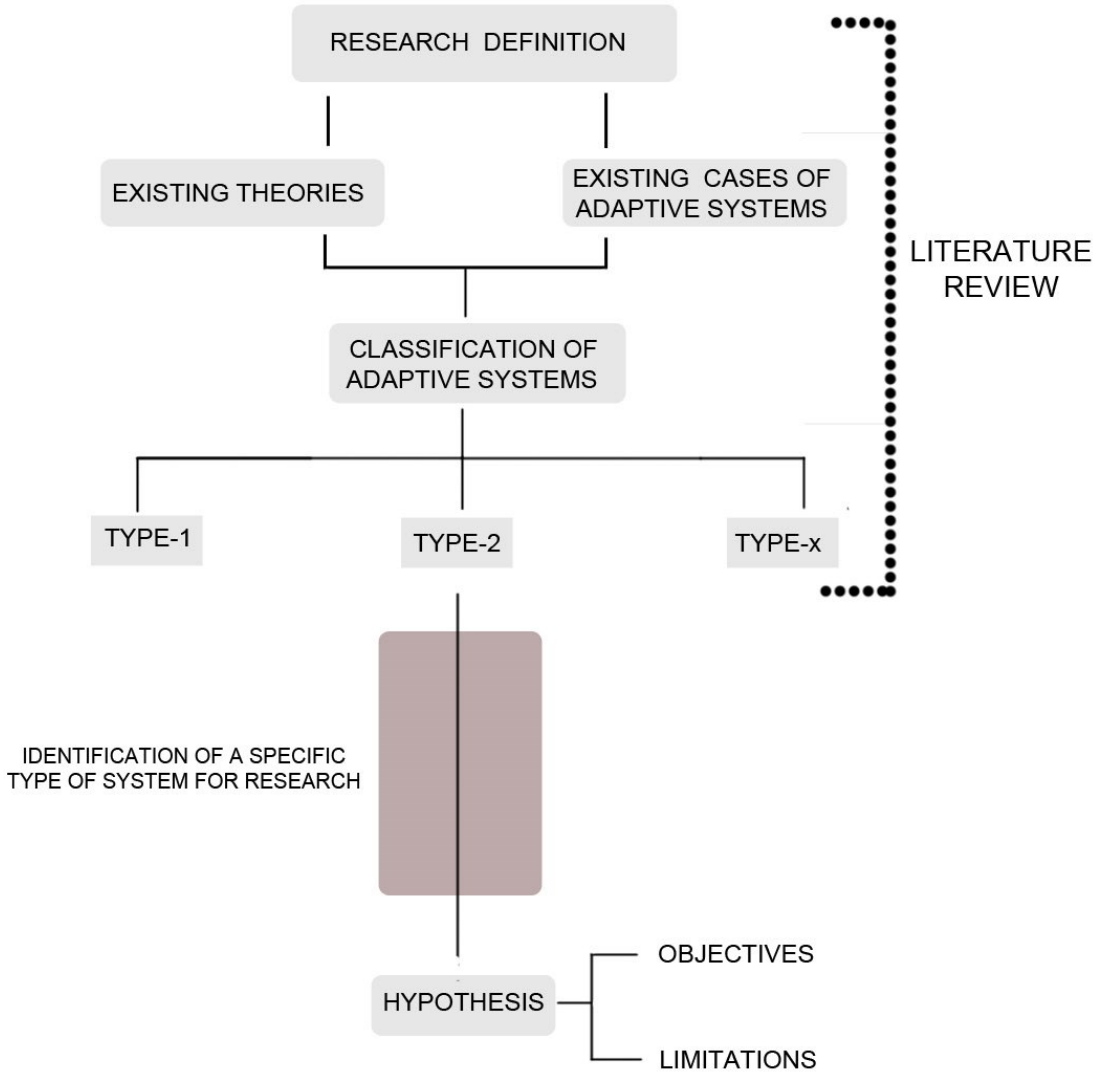

Fig. 3: Research Methodology process from the research idea through literature review to hypothesis formation

Simulation models will be developed in Ecotect for the various possible configurations for each of the adaptive system. The south facing orientation will be considered for the shading system. In DaySim, the Annual Illuminance Profiles at hourly intervals will be created for each specific static state. Through these profiles, optimized state of the adaptive system will be selected for each hour for an entire year through a custom script

written in java. As a result, we generate an optimized adaptive system with an ideal specific state for each hour for an entire year. This optimized system will be compared with a fixed shading system used as base case(this will be different for each specific adaptive system) in terms of daylighting both quantitatively and qualitatively. This process is repeated for each specific location to understand the benefits and behavior of a adaptive system with respect to geographical location.

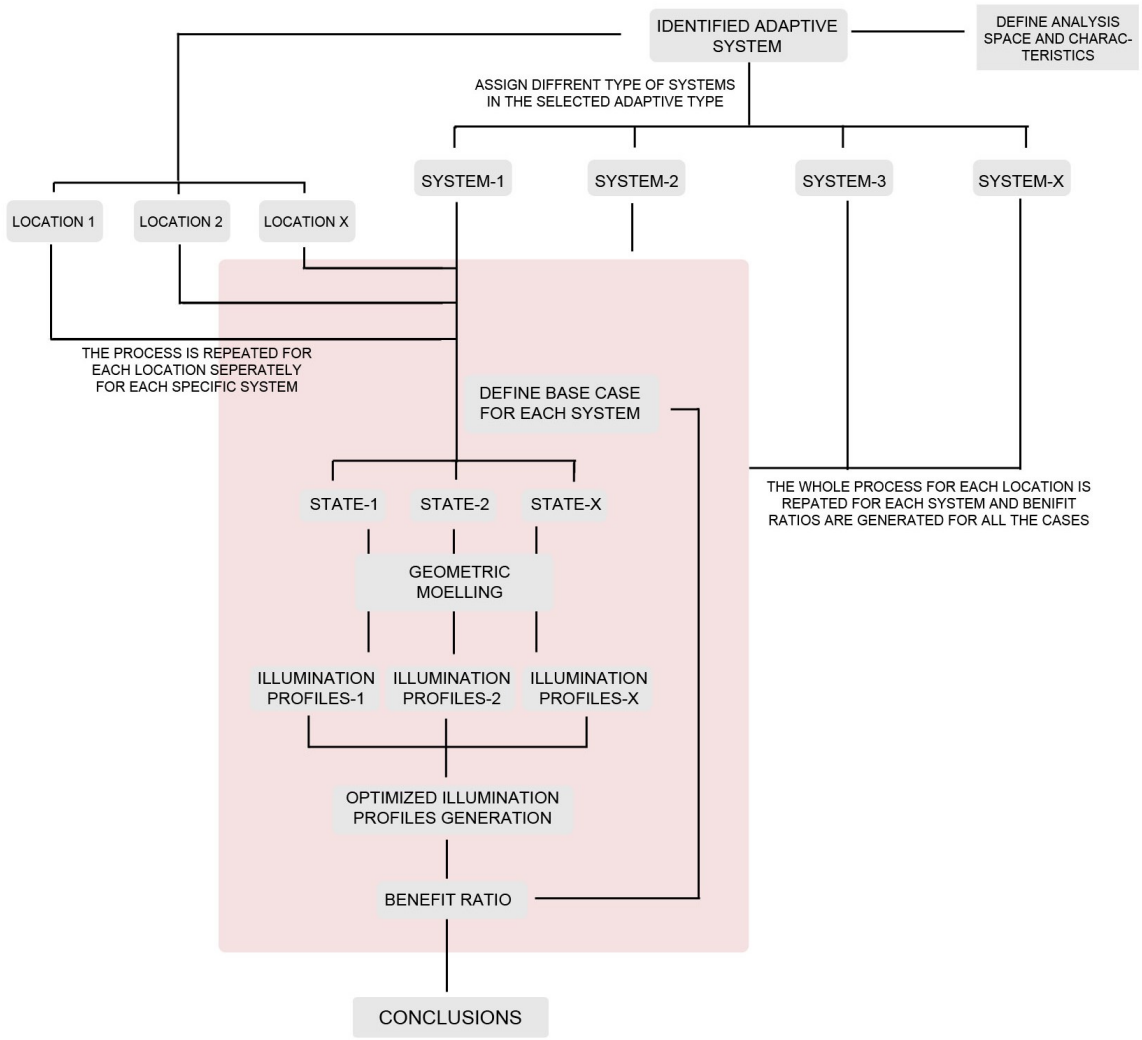

Fig: 2 Research Methodology process through research design and data generation through simulation process and benefit analysis by comparing with the base cases and finally the conclusion

Benefit ratios will be generated for each of the different adaptive systems pertaining to each location. Conclusions will be drawn on the benefits with respect to the adaptive system and geographic location accordingly.

Adaptivity is 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 doesn't necessarily facilitate this adaptability to change. We have seen massive changes on the sustainability front in recent times but still the paradigm we follow for designing performance based systems hasn't changed much. To really achieve the full potential of climatic response the paradigm has to change. Conventional Buildings that are designed for static sets of dynamic factors often create a disjunction between the building and its environments. 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 ever changing environmental conditions thus providing better efficiency than static systems.

This research is an exploration into Adaptive Building skins to achieve specific architectural goals. The Architectural goal would be to develop an Adaptive skin, independent and intelligent which would evolve from its own history of responses and learn from these to reach a certain level of optimization in terms of efficiency. The possibilities of incorporating cellular automata, genetic algorithms, artificial neural networks and optimization principles to achieve an emergent behavior will be studied. This adaptive skin will be responsive to a set of dynamic factors like environmental data and site specific user modifications of the space. User response is often neglected in the current examples of adaptive systems and this research will look into the level of control a user can have on the system and also how the user input will be incorporated and drive the system to a certain level of optimization. This research assumes that the static site conditions remain the same and any change in these conditions have to be input

manually. The achievement of these goals will lead to a highly adaptive and performative Architectural System.

3. Classification of Adaptive systems

Adaptivity systems have been broadly divided into four different types based on the level of adaptivity i.e. if the skin is adaptive or if the entire structure is adaptive or if the adaptivity is in other forms.

1 .Dynamic Facades and Intelligent Surfaces

Sensory based Responsive architecture includes dynamic facades and responsive surfaces. Most of the adaptivity work is done is this classification, as it is easy to separate the functionality of the non-adaptive parts of the building from the adaptive parts itself.

2. Transformable Structures

This second level of adaptivity involves entire buildings which adapt over the longer term to changing economic demands, weather patterns, emergencies and other external factors. This sort of adaptivity has yet to be realized in larger scope as several economic, functional, technological challenges faced by the systems are yet to be resolved or realized.

3. Smart Materials

"Architects who fail to run with the trend sparked by radical smart materials towards adaptive and kinetic buildings will be left behind". Axel Ritter (Architect, Ritter Architects based in Virginia)

Materials whose properties can be significantly changed in a controlled manner by external stimuli such as temperature, electric or magnetic fields can be considered as Smart materials. The progress made in the science of smart materials is dependent upon the advances in the material sciences. The use of materials that change their properties in reaction to heat, moisture or light can hugely change how we conceive Architecture. The key considerations with respect to smart materials would be if the changes are reversible or not. They could be as simple as paints which change color based on the temperature.

Smart Materials can be broadly divided into

Color Changing Materials

Photochromic materials: These materials change color reversibly with respect to light intensity. They are generally colorless in dark and in Light the molecular structure changes and they show exhibit color.

Thermochromic materials: The color change is dependent on temperature. The color change depending on the material happens at a certain temperature

Light Emitting Materials

Electroluminescent materials: They produce different colors when stimulated electronically.

Fluorescent materials: Produce visible and invisible light when the incident light is of a shorter wavelength and the effect is gone after sometime.

Phosphorescent materials: Very similar to the Fluorescent material

All the above materials have aesthetic qualities but functionally for adaptive systems they are less useful. But the following category has a huge role to play as technological advances are made

Moving Materials

Conducting Polymers: The very characteristic of these materials is electrical and chemical energies are transformed into mechanical energies and when electricity is passed electrons and ions are transferred from one end to the other as a resulting in bending on one side and expansion on the other side.

Shape Memory Alloys: Metals which change shape due to the strain created at a certain temperature and revert back to original shape afterwards due a change in the crystal structure. Large strains can be created depending on the material.

Dielectric elastomers: Under electric field they exhibit mechanical strain. The material expands under an electric field and comes back to normal shape after discharge

4. System Intelligence

System Intelligence of a building can be at two levels. First level of is the programmed reaction of the building to the changing environmental conditions. Most of the buildings especially the buildings with larger footprint are competent at this level. But the second level of system intelligence would be user specific response or occupant override

capabilities and also the system should be 'intelligent' and 'emergent'; capable to learn from the set of user responses and future weather patterns and change accordingly. It should also have the capability of learning from any of the mistakes made in the system in the long run. Thanks to the large number of data streams available, weather data from the past century can be used to forecast the future weather patterns and also the centralization of the building systems which have been transformed by the ubiquitous communication technologies has given a big scope in improving the building intelligence. To make use of the data entirely and not only optimize it but also learn from the data is imperative to make efficient buildings. Even if we are considering a building with minimal adaptivity there is a tremendous scope for use of Building intelligence.

Adaptive Shading Systems

The development of a adaptive system can be categorized into the following parts. While Analysis and Design are the very basis in the development of any system. User Interface adds further complexity to the process. The role of the user varies from being someone who simply changes the output of the system to someone who is involved in the development process itself which decides the final output. Finally Artificial Intelligence would be the most complicated layer which would give the system ingenuity to develop over a period of time .

4. Case Studies

Arab World Institute

This is one of the first buildings to employ an automated adaptive system connected to the sensors. Based on the sensors readings of the environment conditions the system generates an automated response. This treatment is on the south side divided into 240 sub grids which consist of photosensitive mechanical devices and act like automated irises to control light. There are about thirty thousand sensors sensitive to light and 1600 diaphragms elements which function like a lens of the camera. All the mechanical devices are connected to central computer which based on the light quality inside the building open or close incrementally. This screen draws inspiration from lattice work found in Middle East in patios and balconies. The building focus is on lines and play of light which are accentuated with the adaptive system which does an aesthetic role. (Arab World Institute, 1989)

Figure 4: Arab World Institute Facade

Observations

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

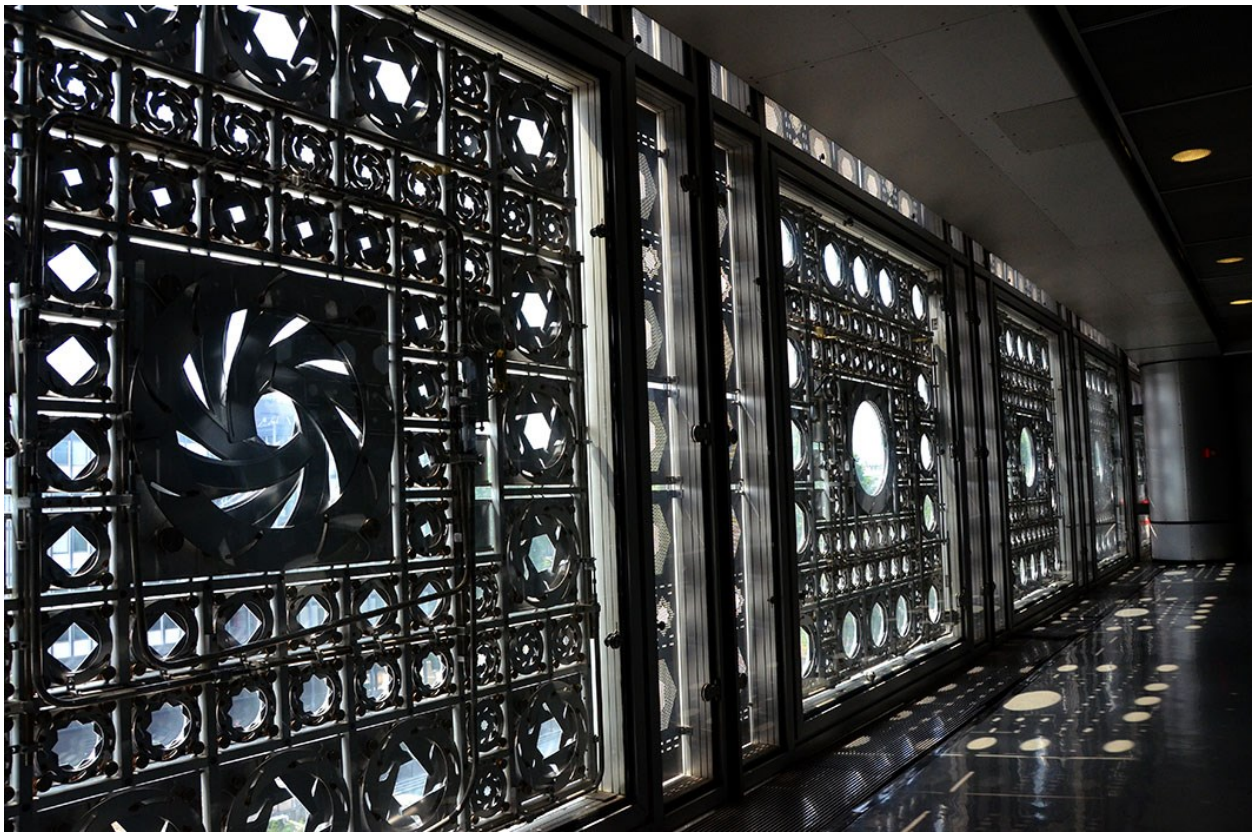

Figure 5: Diaphragms in the Façade which act as lens

GSW Headquarters

Figure 6: GSW Headquarters Façade

The striking design feature of the building and also the adaptive system of the building is the façade .The east side has automatically operated triple-glazed windows which can manually override the automatic movements. The west side consists of a double – skin that also have the similar features of automatic operation which can overridden if necessary manually. On the west façade wide, vertical, perforated aluminum louvers of various colors ranging from red to pink to orange are located and provides external solar shading. On Sunny days the colored elements complement one another into a colored carpet shade the entire west façade. The double glass on the West façade allows for a

natural air conditioning through a chimney effect caused by cross ventilation. This results in significant reduction of energy usage. (Russell, 2001)

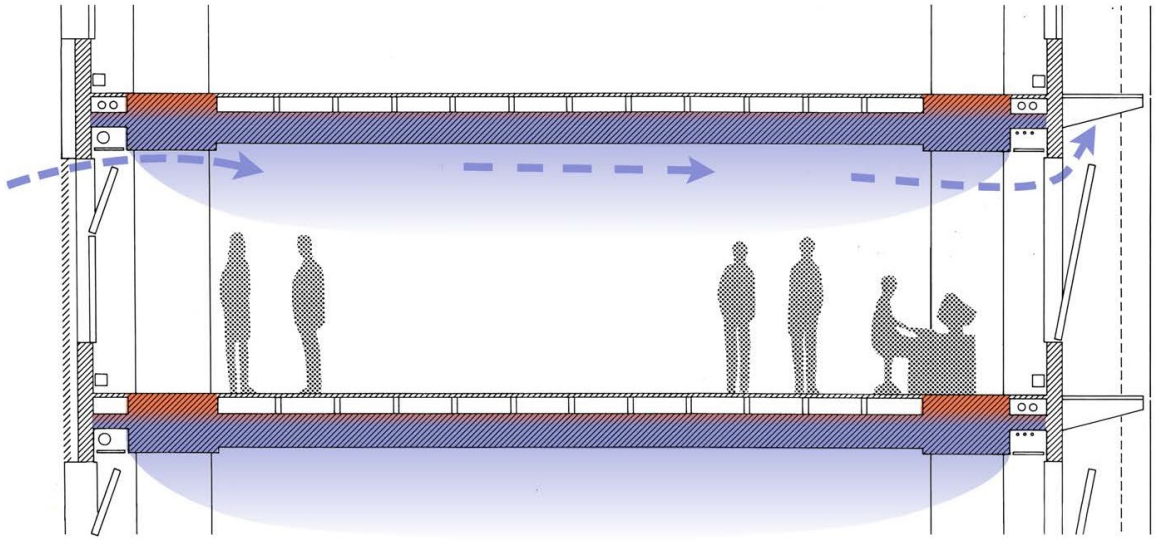

Figure 7: Cross Ventilation enabled in the building because of adaptive elements

Building Management System:

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 considered sufficient. This is a real time system. It also controls the colored louvers on the west façade automatically. Another important feature is manual provision for override. The users can override the system through zonal controls provided at all the window sill levels. 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 8: Manual User Override controls

Observations

This is one of the very few buildings which not only gives user manual control over the automated building management but also gives feedback to the user while the override is made. Considering this building was built 15 years back these user controls can be replaced in new buildings using mobile devices which enable more freedom in not only the override process but also enables to give more detailed feedback on the decisions being made by the user. This system is more advanced than the entry level system intelligence but it doesn't have any emergent system which learns from the decisions being made by the user nor does it have any specific behavior with respect to future weather patterns.

Figure 9: Automated Louvers integrated into the façade of the building

Tesselate and Adaptive Fritting

Tessalate and Adaptive Fritting are few of the various intelligent surfaces being developed by Adaptive Building Initiative which is collaboration between Hoberman Associates and Buro Happold. Both of these systems are based on the same concept of modules that rotate around a pin thus enabling different levels of Transparency. When

the patterns are aligned with each other it gives us maximum transparency and on the other end it becomes an opaque system, thus enabling the building of functional capacity to dynamically change its Transparency and thus creating interesting lighting quality sculptive in nature not only in aesthetic point of view but also enables the system to be sustainably efficient.

The Surface can be divided into sub panels in which each panel has motor which communicates with a Computer thus enabling control of speed and acceleration of the movement of the panels. Any sensor input can also be linked thus enabling a direct link with any environmental changes like temperature. So we have direct control over shading, solar gain and glare, ventilation and air flow control. All the panels can be customized to non-standard free form patterns. It can be used as an element in facades, roofs, awnings or independent surfaces because of its sculptural quality.

Adaptive Fritting

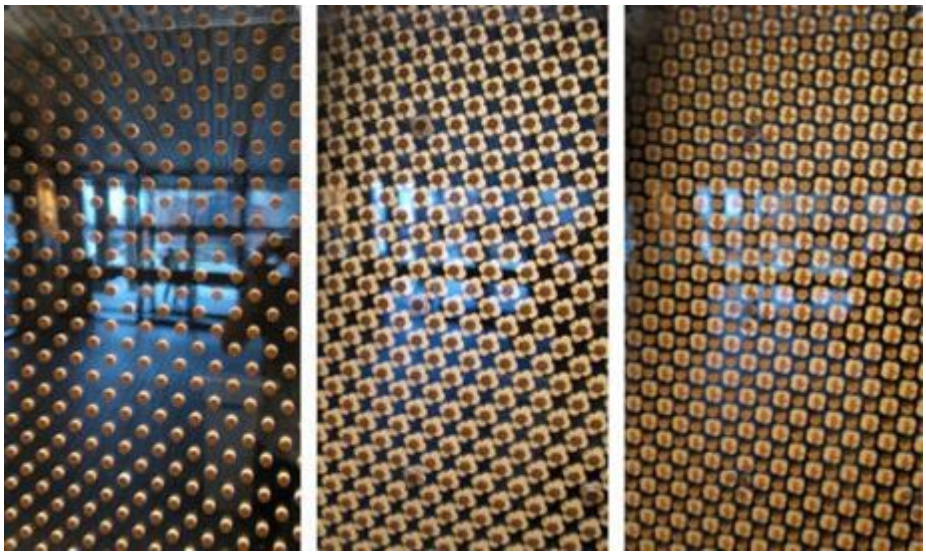

Figure 10: Adaptive Fritting

"Adaptive Fritting™ is an integrated glass unit with a custom moveable graphic pattern that can modulate its transparency to control transmitted light, solar gain, privacy, and views.'' (Adaptive Building Initiative, 2008)

The change from opaque to transparency states is achieved by moving a series of fritted glass layers so that the pattern align and diverge. The control of the patterns is infinite as even organic and non-repeating patterns can be integrated.

Tessellate, Stony Brook Foundation

"Tessellate is a self-contained, framed screen whose perforated pattern can continually shift and evolve; creating a dynamic architectural element that regulates light and solar gain, ventilation and airflow, privacy, and views." (Adaptive Building Initiative, 2008)

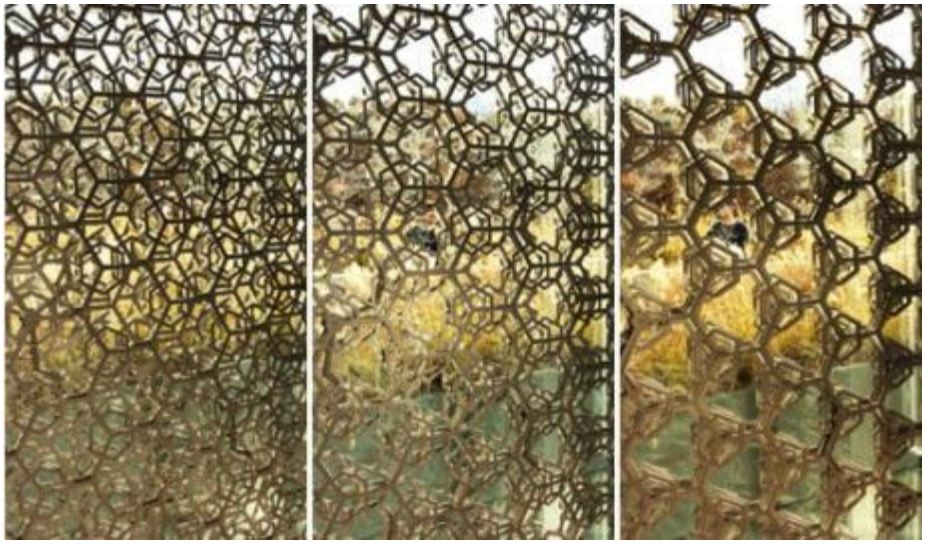

Figure 11: Tesselate

Observations

Both Tessellate and Adaptive Fritting are independent systems and scalable. As a result they have an inherent advantage that they can be fitted into any existing or new setting.

This is also helped by the good customization of the products available which enables the architect to decide on the shape and pattern to suit his specific needs. The other advantage is the system behavior can be modified or upgraded in future to respond to changes with the same adaptive system intact.

Q1

The main function of the façade system is control the entry of light into the building. The shading system which look like metal feathers are actually made of 3,150 stainless steel movable vertical elements into which stainless steel louvers are fitted. These rotatable elements which are linearly motor driven represent an optimized system which takes the advantage of the horizontal lovers with the adaptive vertical elements. The basic operations are closing when the elements are parallel to the surface and open when the system is perpendicular and third being the follow of the position of the sun, perpendicular to the angle of entry of the sun. They move accordingly to the angle of the sun reducing the requirement of artificial lighting and also air-conditioning and climate control thus creating a very sustainable and energy efficient system. Apart from the energy efficiency the façade defines the character of the building. (Purzer, 2011)

Figure 12: Q1 Building Facade

Observations

There is no individual user involvement in the system. As a result the system is easier to optimize for high energy gains but the preferences of the user are completely undermined. As a result based on this preference at that specific time he cannot decide if he wants the louvers open or closed or at any specific angle.

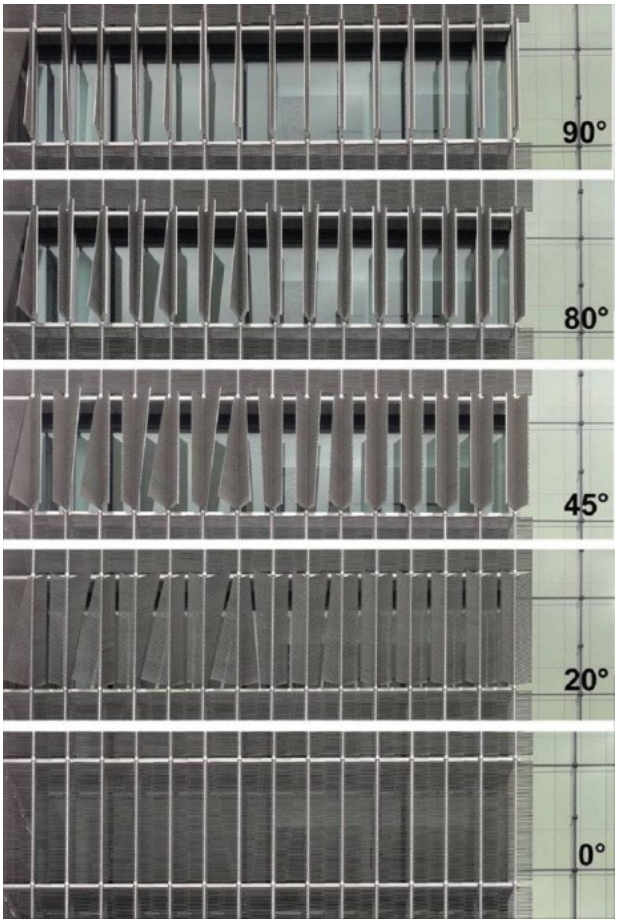

Figure 13: Various Possible Louver Angles in Q1 Building Facade

Homeo Static Façade Syste**m**

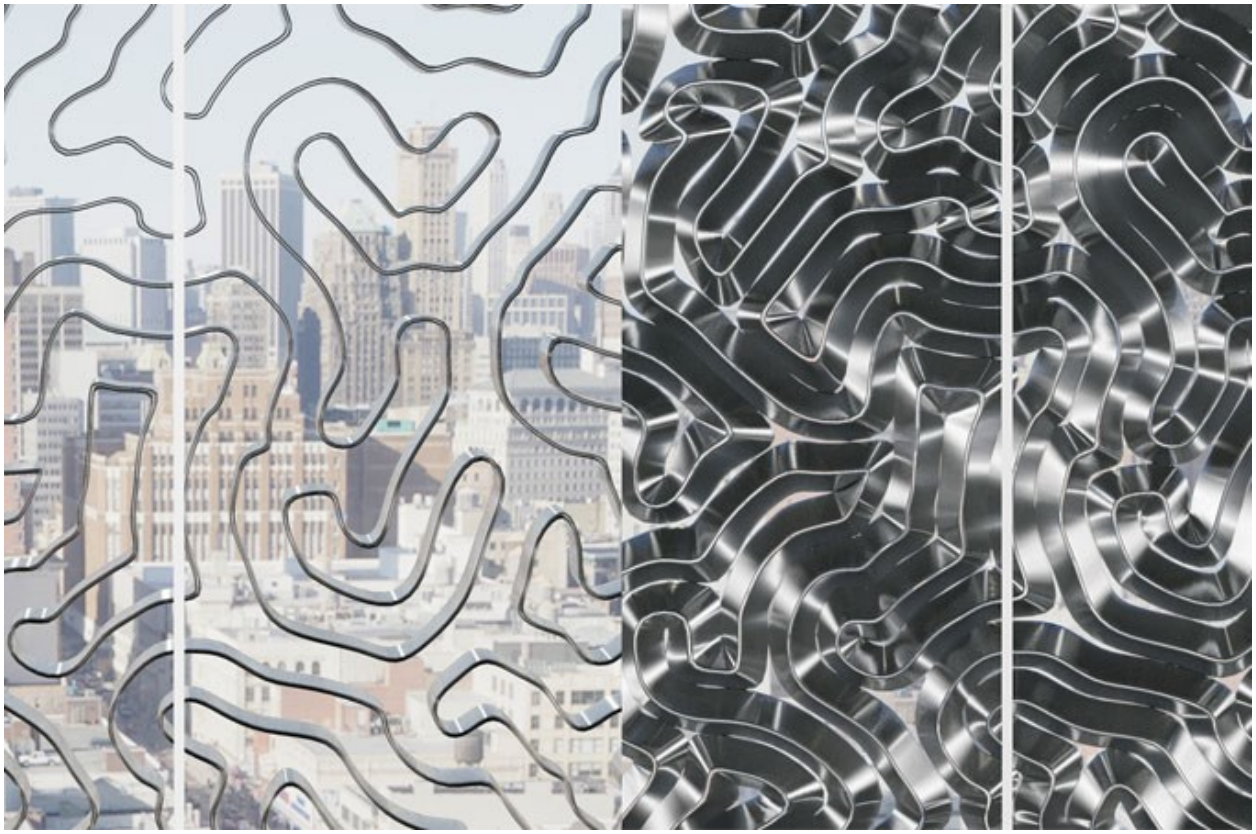

Figure 14: Open and Closed positions of Homeo Static Façade System

Homeostasis is a natural phenomenon where different organisms regulate the internal conditions through different actions. Human sweat is such a response to heat. The screen is based on the principle of dielectric elastomers which allows the building façade system to control the solar gains. This system is developed by research based Architectural practice firm, Decker Yeadon based in New York. The façade regulates the internal conditions by responding to the environmental conditions. The polymer and elastomer 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 polymer. Thus this system controls the thermal flow thus regulating the internal building temperature. (Decker Y.)

Observations

The system is highly responsive even to the smallest of changes as it is able to respond to changes which happen in real-time like the sun going behind the clouds and the shadows of the neighboring building. As the system doesn't need any sensors or any electrical power consumption to work it offers great levels of energy efficiency. But this system is very rigid as the user has no control whatsoever on the system and can't change according to his mood and need. Say on a sunny day if the user wants the screen fully open to let in light ,the Homeo Static façade system wouldn't be able to do that and will open partially because the sunlight levels are low. Similarly in hot climates you might need it to close even when the sunlight levels are low which is not possible through the system. As the system is only responsive to temperature it can only be fully responsive as an auxiliary system.

Smart Screen

Figure 15: Rendering of Smart Screen Façade System

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 material is responsive to ambient room temperature and doesn't require any sensors, motors or even electricity as it is thermo responsive to operate and regulates the heat transfer. All the material closes as the temperature rises and opens the apertures when the room is cooler to allow heat gain. This system is also developed by research based Architectural practice firm, Decker Yeadon. (Decker Y.)

Observations

Similar to the Homeo Static System the Smart Screen is very rigid as user doesn't have any role in if the system opens or closes. As it is only temperature specific it has to be used as a secondary system to be fully responsive. But it has the advantages of being very highly responsive as the surface itself is the motor and will work with zero power consumption for the system

5. Metrics: Quantitative and Qualitative

It is important to look at metrics to be used in the analysis. The Metrics used influence the outcome of the analysis. The analysis outcome can be positive in some metrics and turn out to be

Daylight factor: This concept is probably is the oldest and probably 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 overcast skies. It is calculated at the horizontal work plane illumination

Daylight Autonomy:

This concept is the first metric annualized thus enabling the possibility of incorporating adaptive systems as it can't be calculated and optimized for a singular time interval. It is the percentage of annual daytime hours that are above a specified illumination level. It also allows the possibility to change the threshold values unlike daylight factor.

Continuous daylight Autonomy:

Unlike daylight Autonomy which doesn't use the values below the threshold used Continuous Daylight Autonomy gives partial credit to values below the user defined threshold.

Useful daylight Illuminance

This is a modification of Daylight Autonomy and based upon three illumination ranges, 0-100 lux, 100-2000 lux, and over 2000 lux. 0-100 and > 2000 get partial credits too.

Temporal Daylight Autonomy:

This is the fraction of time 75% of the space has over the specified illuminance level.

Spatial daylight Autonomy:

This metric reports the % of sensors that are above the minimum daylight illuminance level for a minimum percentage of the time over a year. This value is generally taken at least as 50%.

Most of the above metrics are quantitative though they give slight idea qualitatively. The most used qualitative aspect is calculation of glare in a space but this metric is avoided in this research as glare is calculated in a specific view and it is very difficult when you are generating values for every 30 min or 1 hour time intervals. So instead the following Qualitative metrics are considered.

Daylight Uniformity:

Coefficient of variation gives a good idea about the uniformity of light in space. Similarly a maximum to average of average to minimum calculation gives insight into the uniformity of Daylighting. Both these metrics are used to calculate the qualitative aspect of the analysis.

To take advantage of the adaptive system fully and to fully highlight the potential a use a combination of Spatial daylight Autonomy and Useful daylight Illuminance is used.

Metrics adopted for Analysis.

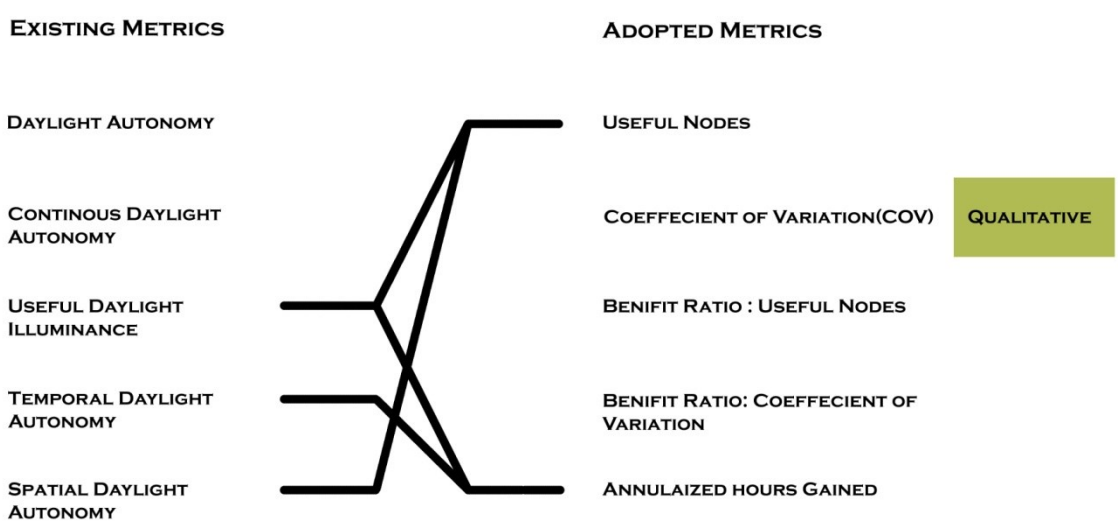

Figure 16: Adopted Metrics with respective existing metrics

Quantitative Metrics:

Maximum Useful Nodes:

This is the % of nodal or sensor points in the spaces analyzed that are between the specified maximum and minimum threshold values. For example the threshold values used in the analysis are 200 and 2000 minimum and maximum respectively.

Average Illuminance:

This is not a good metric to understand the lighting in a space but it is included in the analysis as it gives insight into the lighting levels when evaluated along with Maximum Useful Nodes.

Qualitative Metrics:

Coefficient of Variation:

This has been calculated to analyze the qualitative aspect of daylighting in terms of daylighting uniformity. Higher coefficients generally mean that there is a big variation in Daylighting levels.

COV = Standard Deviation/Mean

Uniformity Factor:

This is another Qualitative aspect considered in the analysis calculated through maximum to average of average to minimum calculation.

6. Analysis and Development process

There are several layers to the development process in analyzing the daylighting in the space both qualitatively and quantitatively.

Layer-1: Select the appropriate daylighting metric which showcases the full potential of the system. Taking multiple metrics is helps in preventing any bias towards one specific metric.. The necessary simulations are done to produce the Annual Daylighting Profile in DaySim through Ecotect. The Illuminance values are calculated for the space for every node point all throughout the year. Through scripting, these values are used to generate optimized conditions for maximum useful nodes

Layer-2: Further calculations are done to calculate Average illuminance and Coefficient of variation to supplement the qualitative analysis too. Optimized values are generated for these specific metrics too.

Layer-3: To make the system more intelligent threshold are incorporated while generating optimized values. For Example, if a threshold of 10lux is given while generating optimized values for maximum useful nodes, if there is a position at specific time interval it wouldn't change unless there is a loss/gain of 10 lux w.r.t the best position

possible. Thus the system avoids movements with minimal gains and in turn saving energy. Additionally, different time intervals are also analyzed to see

Layer-4: A weighted profile has to be generated to combine Maximum Useful Nodes, Average Illuminance and Coefficient of variation and optimize them together. And also the numbers of changes happening in a day in an optimized case are kept track of. 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 maintaining the system.

Layer-5: the Final layer would be to incorporate Artificial Intelligence Algorithms to enable the system to become self-aware and to keep growing over time. A feedback loop should also be enabled to interact and respond to the users of the space. This layer will not be incorporated into the process in this research and will be left for future exploration

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 adaptive shading and extent of adaptivity

being analyzed

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Case 1200 A+E

Space Definition: A 12m x 5m space with a single long horizontal window on the Southside with the Sill at 900mm and the height of the window is 1300mm.

Static Shading:800mm deep

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

Case 1200E

Space Definition: A 12m x 5m space with a single long horizontal window on the Southside with the Sill at 900mm and the height of the window is 1300mm.

Static Shading: 800mm deep

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

Case 800A+E

Space Definition: A 12m x 5m space with a single long horizontal window on the Southside with the Sill at 900mm and the height of the window is 1300mm.

Static Shading: 800mm deep

Type of Adaptivity: The shading device will be able to change it angle when it is in 800mm position. The possible angles are 30 degreed up and down and 60 degrees up and down.

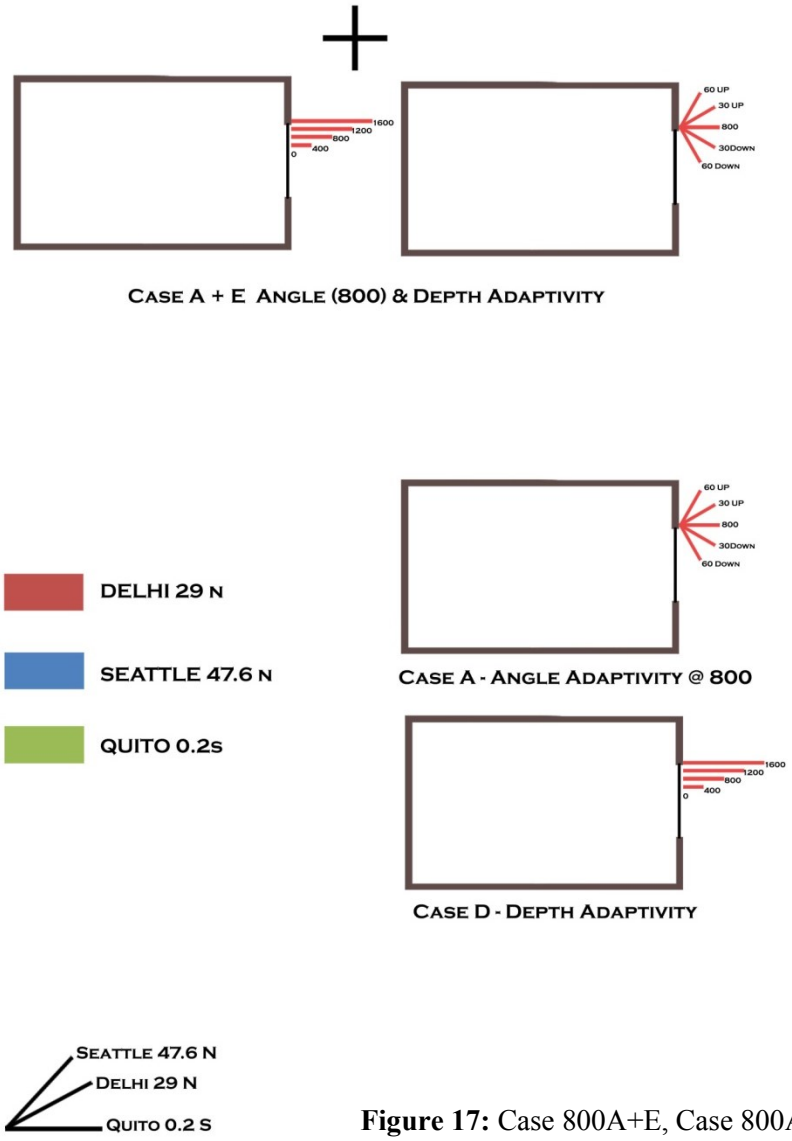

Figure 17: Case 800A+E, Case 800A, Case 800E(Depth Adaptivity)

Case 800E:

Space Definition: Static Shading: 800mm deep

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

Case 800A:

Space Definition: Static Shading: 800mm deep

Type of Adaptivity: The shading device will be able to change it angle when it is in 800mm position. The possible angles are 30 degreed up and down and 60 degrees up and down.

Case F:

Space Definition: Static Shading: 800mm deep

Type of Adaptivity: The Opacity of the window changes

7. Analysis Results

Initial Results

Case 800A+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. 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 (Fig 18a). 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 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 (Fig 18). 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 18a: Case 800+E Number of Nodes, Delhi

Figure 18: Case 800+E COV, Delhi

Final Analysis Results

On the strength of the initial results, the full suite of simulations was run. The important Observations from those results are presented here.

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

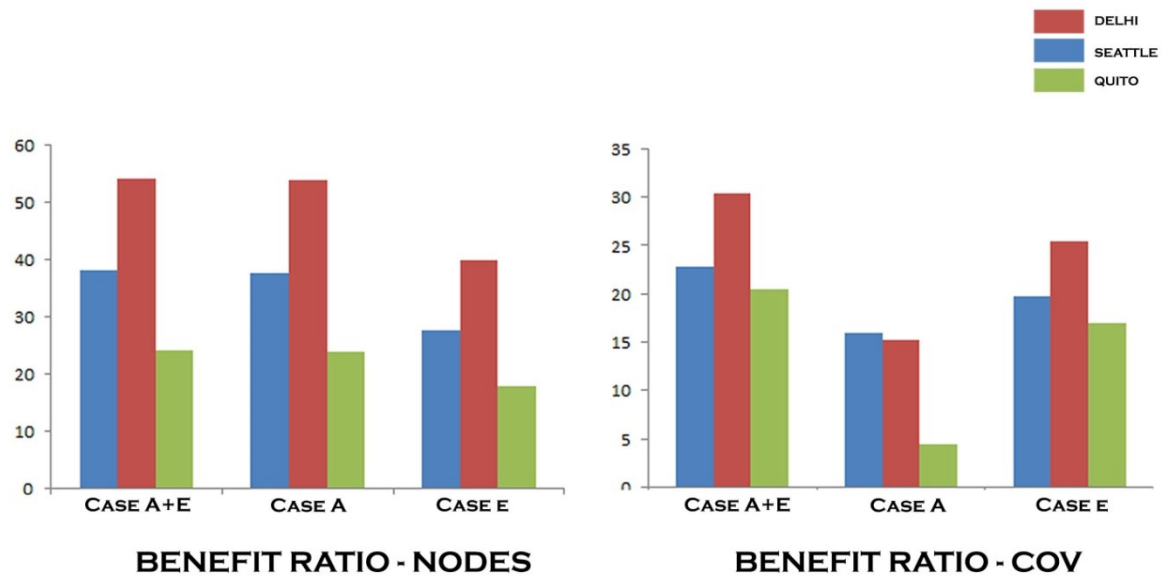

Figure 19: Case 800A+E, Case 800A, Case 800E: Benefit Ratio Useful Nodes, COV

The benefit ratio for useful nodes was highest in Case 800A+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 800 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 (Fig 19). In Annual Daylit hours, the maximum hours are gained in Delhi with Seattle and Quito have similar but lesser improvements.(Fig 20)

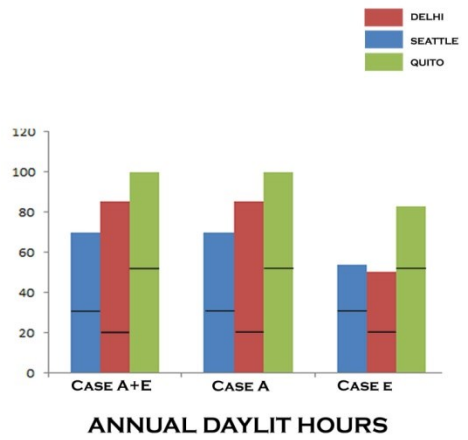

Figure 20: Case800+E, Case 800A, Case 800 E :

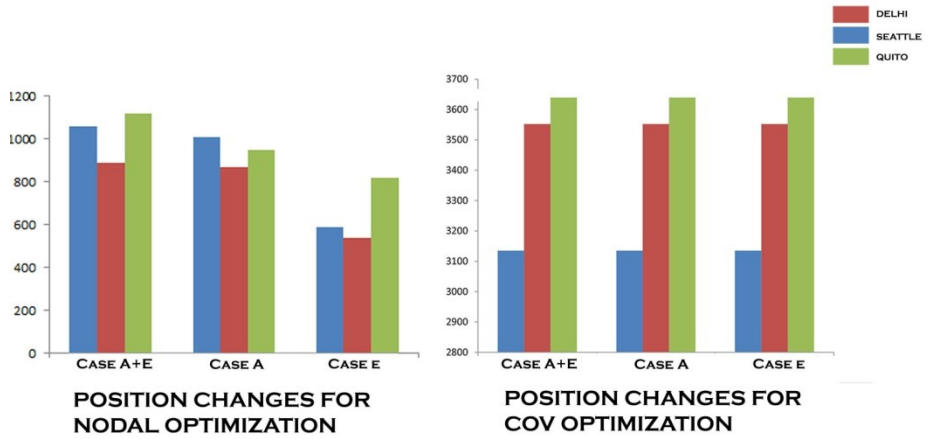

Figure 21: Case800A+E, Case 800A, Case 800 E : Position Changes

Above figure (Fig 21) shows the daylit hours in optimized dynamic positions while the markings indicate the static daylit hours. The figure shows the number of position changes for each metric for optimization. In Nodal optimization of Case 800 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 (Fig 22) the annualized number of changes in a day for nodal optimization. The general number of changes in a day varies from 0 to 7.

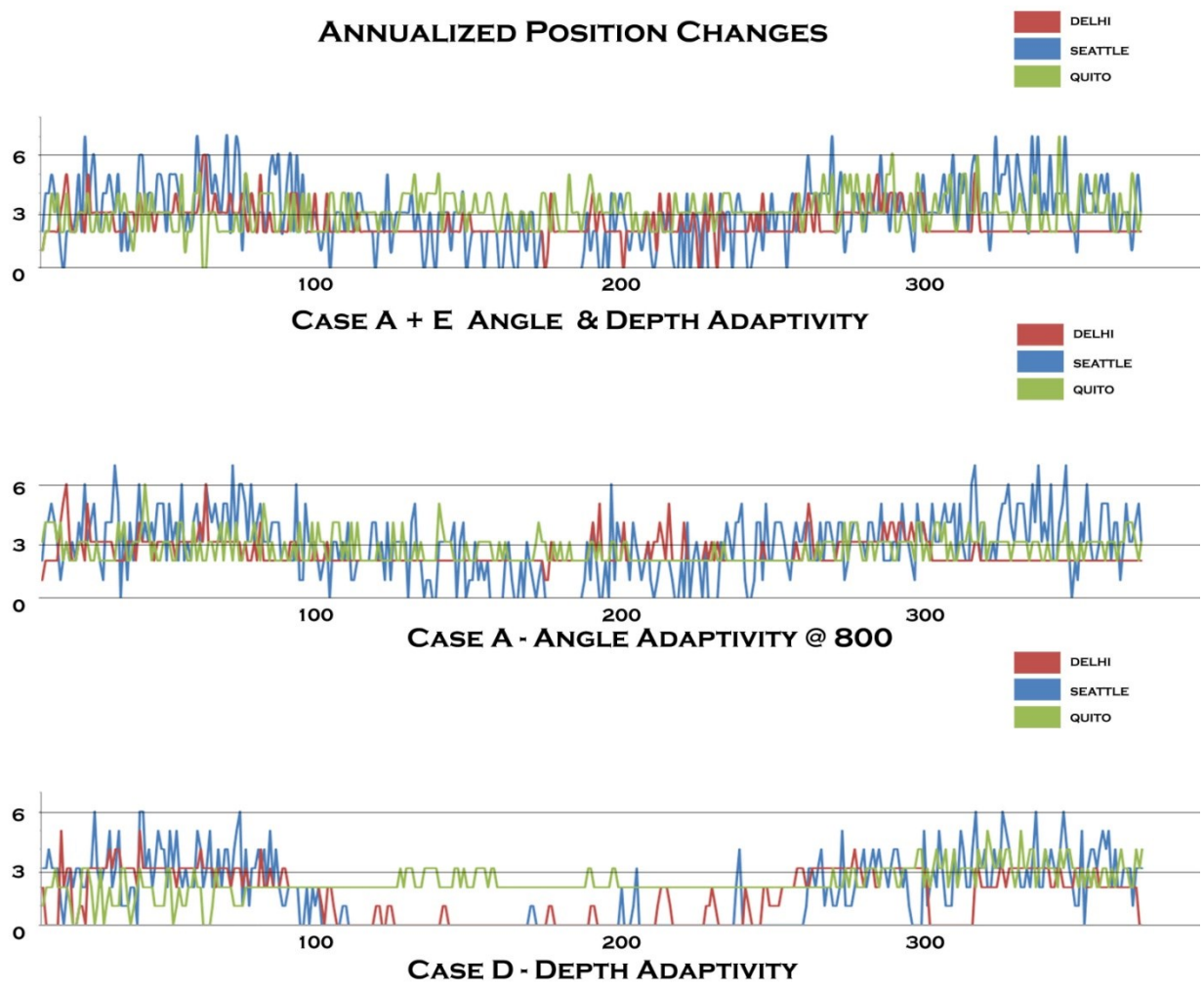

Figure 22: Case800A+E, Case 800A, Case E: Annualized Position Changes for Nodal Optimization

This figure shows the annualized benefit ratio for useful nodes (Fig 24) and COV (Fig 23). 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.

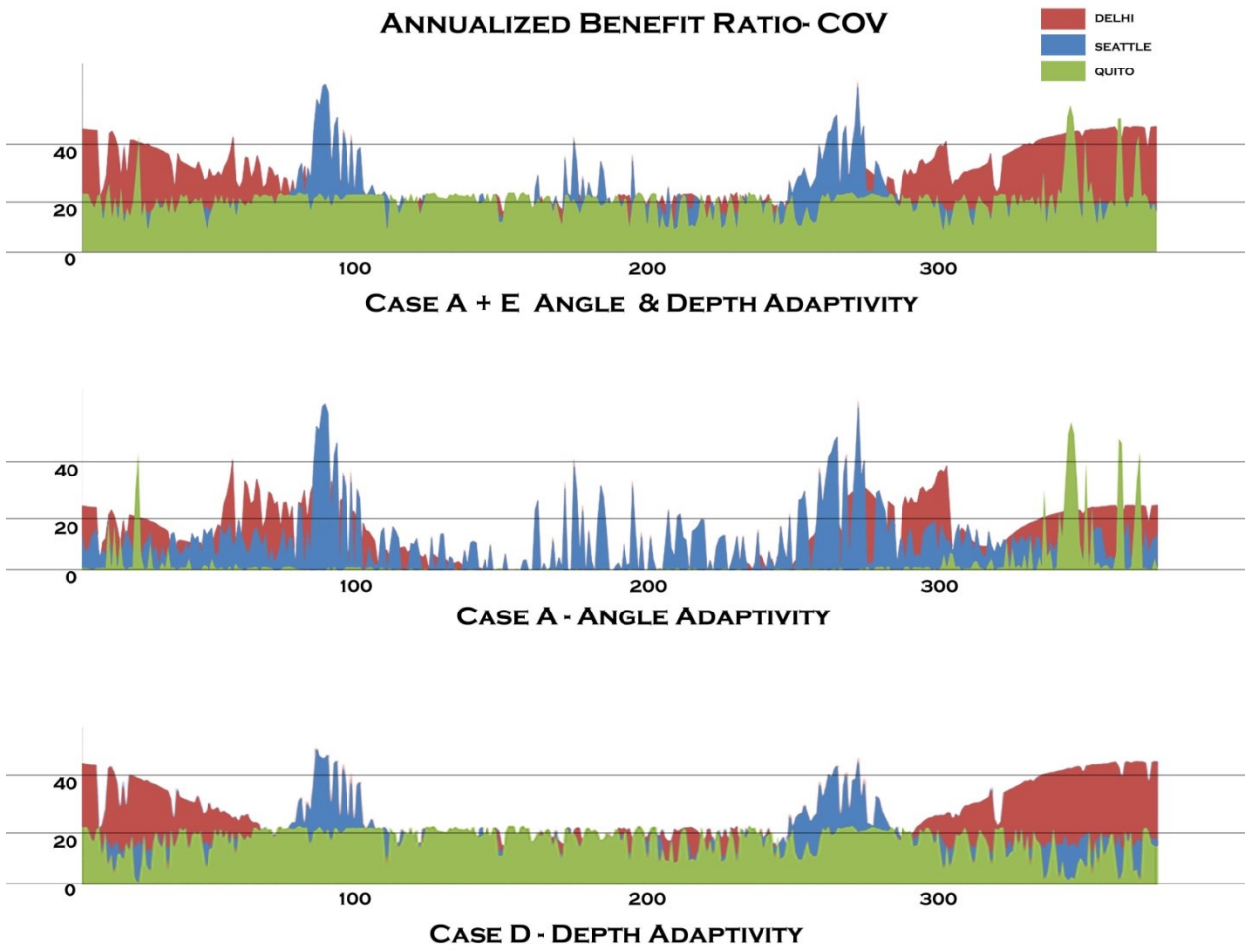

Figure 23: Case800A+E, Case 800A, Case 800 E: Annualized Benefit Ratio: Useful Nodes

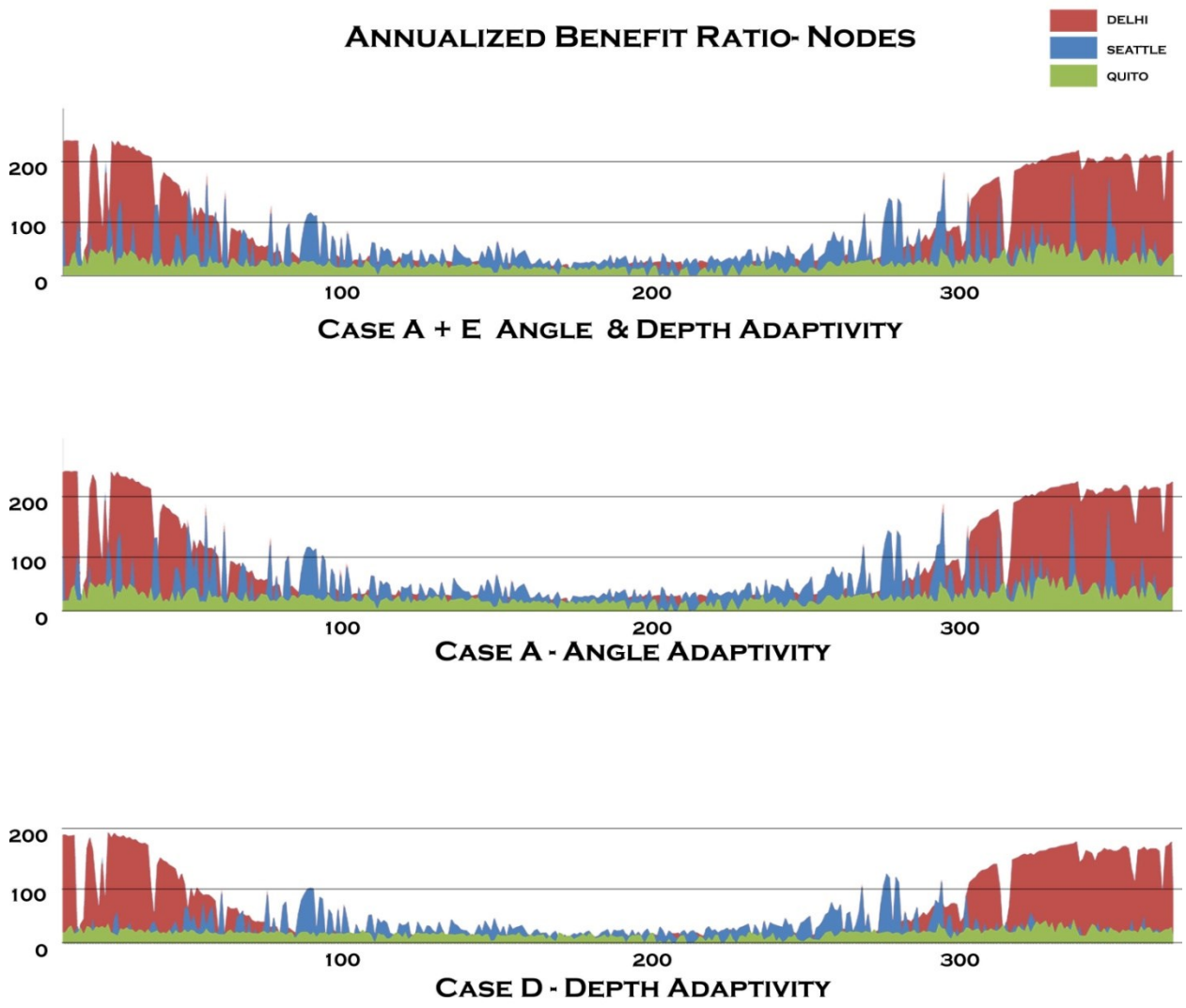

Figure 24: Case 800A+E Case 800A Case E : Annualized Benefit Ratio: COV

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

In this scenario, when the dynamic configuration is compared to a static configuration of depth 1200mm the benefit ratios for both Nodes and COV(Fig 26) are less when compared to the previous scenario(Case 800A+E). Similarly, the benefit in annual daylit hours is also less (Fig 25). But the general patterns in both the scenarios (Case 1200A+E, Case 800A+E) remain similar.

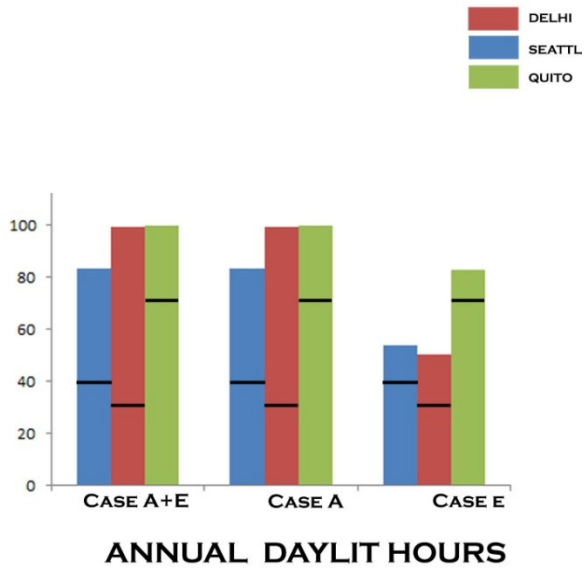

Figure 25: Case 1200A+E, Case 1200A, Case 1200E : Benefit Ratio

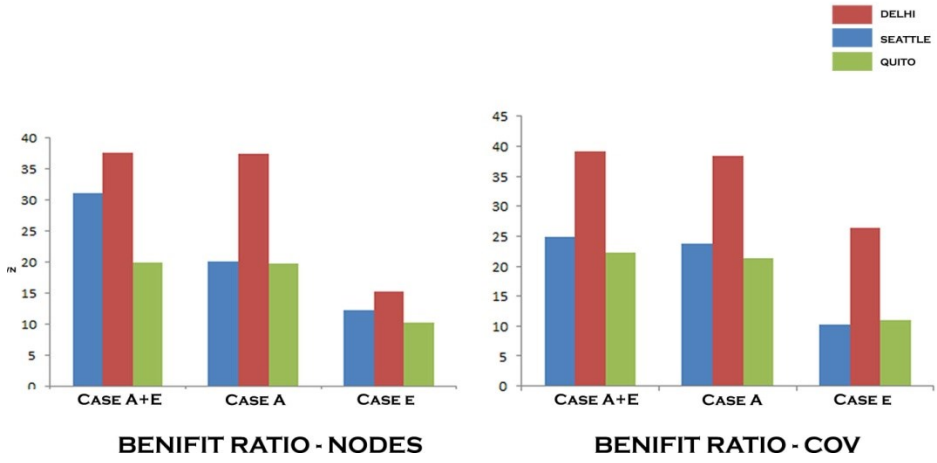

Figure 26: Case 1200A+E, Case 1200A, Case 1200E: Annual Daylit

8. Conclusions:

The principle motivation behind this exploration was to encourage the consideration of adaptive 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 adaptive shading is a highly sustainable solution in Delhi. Even Seattle has decent gains, but in Quito the gains are comparatively lesser. As a result, adaptive 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%.

Future directions will also include the study of other adaptive 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.

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