HIGH ENERGY EFFICIENT BUILDING ENVELOPE DESIGN WITH INTEGRATED WORKFLOW IN MULTIDISCIPLINARY PERFORMANCE CRITERIA

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SUMMARY

This research demonstrates a practical design method and workflow for low environmental impact and high energy efficient building façade system under interconnected workflow between architecture design and multidisciplinary environmental performance modeling. Although the building façade is one of the most important building elements contributing to energy consumption and occupants' comfort, a practical design methodology to achieve desirable building performance, especially in the early design stage, is not well developed and the applicable design advice tools for performance evaluation and analysis are limited. The latter is caused by the lack of information during the stage as well as the iterative design process which cannot align well with the early design phase which asks to develop and compare various design alternatives in a compressed time schedule. As the complexity of façade design increases and the number of design variables that enter in multidisciplinary performance requirements increases, the informed design decision based on proper integration of performance modeling in the design workflow becomes more critical for architects to assure the performance of project. The integrated workflow presented in this paper utilizes parametric design environments with existing building performance modeling tools. The parametric modeling platform can easily generate various alternatives with different parameters, and it can also simultaneously provide information regarding building performance as result of design parameter updates. This can compress the design cycle time dramatically and help to make proper design decision in considering performance optimization. This paper shows the workflow with a case study which applies this methodology for a small scale office building located in Seoul, Korea where it was required to achieve a multi-criteria performance goal.

CHAPTER 1

INTRODUCTION

In the early 20th century, revolutionary structural simplicity of architecture using concrete and steel allowed the lightness for the building skin system, which brought tremendous flexibility in building plan as well as maximum visual interconnection between indoor and outdoor space. The practical application of the transparent building façade has been accelerated with the technology development in architecture mechanical system, and the state of art HVAC system with automatic environment control system technically can make any building indoor environment always keep in comfortable and benign condition [1]. Therefore, it may not be so surprising to find glass curtain wall building with high performance glazing system even in desert areas such as the Middle East or in Arctic climate areas.

Figure 1. Hyatt Capital Gate Abu Dhabi, UAE

A building that is visually interconnected with the surrounding environment, however, is ironically creating an isolation from the local environment condition, which cause not only the general criticism regarding the contribution to global environmental harm and missing the local identity but also poses sever challenges to achieve acceptable building performances at acceptable cost. As energy cost increase and the concerns regarding global warming are spreading, the need for buildings with high energy efficiency and low environmental impact has become even more critical issue. In most of current architecture practice, the energy performance issues have been solved at the system level by providing high efficiency systems, high performance equipment and building materials, and renewable energy technologies. As a result of this architects may have assumed that no matter what they design, engineering counterparts and other consultants will be able to make their ideas work at the building systems level [2]. High performance building codes like CALGreen and the International Green Construction Code (IgCC), as well as many local building codes and ordinances, voluntary green building programs such as the 2030 Challenge, are however beginning to show that this long-accepted way of working is not yielding optimal results. A more holistic, collaborative approach to design will become vital as energy and operations costs rise and as energy targets are codified [2].

Such integrated design process does not just aim for quantitative performance improvement but needs to include efficient integration between design and engineering workflow. The various design strategies and their evaluation processes to achieve desirable building performance responding to local climate and environments can propose reasonable design directions, which can lead to a more rational decision making process for various building design factors such as materials, geometry, color, parameters, and fabrication details. It also means that energy is no longer just a systems issue, but can be translated as design matters [2]. In this integrated process, architects are required to take a leading role in high performance building design. It also raises the need for an efficient integration methodology of design workflow with relevant building performance feedback especially during the early design phase with emphasis on a number of decisions which have a strong influence on the performance of the building throughout the rest of the design process [3]. Various building simulation tools are increasingly popular to fulfill important roles as design adviser for this new workflow. As Radfort and Gero noted, the information provided by simulation tools is often evaluative rather than prescriptive, which is more useful with more completed design to predict the actual building performance [4]. Moreover, considering the inherent uncertainties in building simulation tools, the inherently limited information in the early design stages, a design advice tool for decision making with investigation and comparison of various design alternatives under common condition is often preferred over tools that are meant to make accurate predictions of the performance of the building [5]. Building simulation tools that are suitable for objective performance comparison of various design alternatives with minimum expense of time and labor as well as offer convenient linkage with design tools have more advantage at the early design phase than the one that rely on detailed simulation.

To support these observations, this research demonstrates a practical design method and workflow application for a low environmental impact and high energy efficient building façade system. The façade is one of the most important building elements contributing to energy consumption and occupants' comfort, and its design requires an interconnected workflow between architecture design and multidisciplinary environmental performance modeling. As the complexity of façade design is increasing informed design decisions based on proper integration of performance modeling in a design workflow becomes more critical for architects to assure the performance of project.

The integrated workflow presented in this paper utilizes parametric design environments with embedded building performance modeling tools which usually don't ask for high expertise and expensive computation time. The parametric modeling platform can easily generate various alternatives. It simultaneously provides information regarding how the related performance indicators are affected by the design parameter updates. This immediate feedback compresses design cycle time dramatically and helps to make proper design decision in comparing the performances of parameters or alternatives as well as considering multi-criteria performance optimization. The performance based design practice is initiated with a clear definition of performance criteria and their target values. A technical analysis regarding the relationship between the building function and its associated system components is done to define the proper performance indicators and key parameters that mainly affect to the performance. This thesis shows the workflow with a case study which applies this methodology for a small scale office building located in Seoul, Korea required to achieve a multi-criteria performance goal.

CHAPTER 2

PERFORMANCE BASED DESIGN WITH BUILDING SIMULATION

PERFORMANCE BASED DESIGN

According to the definition of Oxford dictionary, performance means the action or process of performing a task or function. It also describes the word as the capabilities of a machine, product, or vehicle. When the definition is narrowed down in terms of business, it is described that the accomplishment of a given task measured against present known standards of accuracy, completeness cost, and speed [6]. Although ‘performance’ has been part of the general vocabulary in engineering for long time, the use of the term ‘Performance based design’ is relatively new. As sustainable building design without compromising occupant comfort and excessive extra cost has become new challenge in the building industry. Concerns over global climate change, depletion of fossil fuel stocks, increasing awareness of relation between indoor environment and the health and wellbeing of the occupants, and consequently their productivity, can be translated into ‘performance’ measures that replace the traditional prescriptive terms to guide design solutions [7]. The European Performance Building Directive (EPBD) supports this trend with a paradigm shift in regulations from individual component and system requirements to a framework for the total energy performance of the building [8]. As many countries are shifting their energy code from traditional prescriptive expressions to minimum performance requirements, architects are offered more flexibility in their design, but building design methodology also needs to adapt to the new paradigm [7].

Kalay proposed a pragmatic design theory using quantifiable 'building performance' for architecture design and evaluation, which proposed a more objective and rational design decision making process contrasting a qualitative traditional, with a subjective and intuitive oriented, process based design methodology [9]. Kalay stated that building design is an iterative process of exploration, in which alternative shapes for fulfilling certain functional traits are suggested and evaluated in a given context. Making an actual design decision relies on the designer's ability to explicitly represent, and then reflect upon, the desirability of the performance of a certain constellation of form, function and context [5]. The simple diagram to show the performance based design workflow represented by Petersen is shown in figure 2.

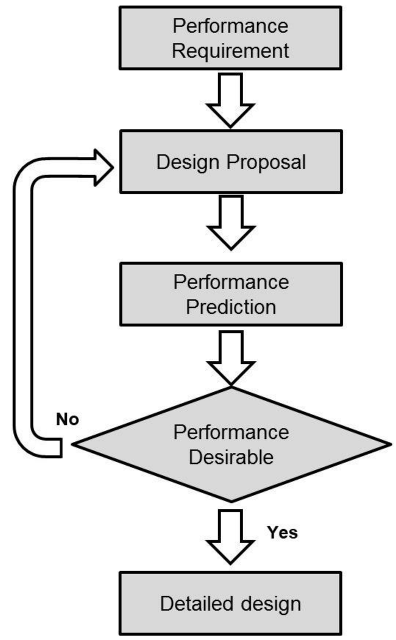


Figure 2. The workflow and subtasks in performance based design by Kalay [5]

The increasing emphasis on building performance – from the cultural and social context to building physics – is influencing building design, its processes and practices, by blurring the distinctions between geometry and analysis, between appearance and performance [10]. As stated above, building performance is not just evaluated with measurement after the construction complete, but is predicted and analyzed by various computer programs from the early design stage onwards, and it can provide objective information for important decision making which tremendously affects total building design. Especially as the demand for reduction in energy consumption and CO_2 emission is intensified and the importance for building operation & maintenance cost has increased, maximizing energy efficiency has become the mandatory requirement in contemporary building, and building design integrating aesthetics and energy performance has become the first concern to the global leading architects. As increased structural flexibility induced new geometry in modern architecture (see figure 3), new opportunities to "play" with the laws of thermodynamics, daylighting, fluid dynamics have become manifest. (see figure 4)

Figure 3. Opera House in Tenerife by Calatrava

New architectural forms fundamentally require more knowledge and dedication to design factors and their translation into the describing parameters, which guide integrated design strategies. Kiel Moe stated on his book 'Integrated design in Contemporary Architecture' that ' now any building project is contingent upon an idiosyncratic assemblage of theoretical, practical, ecological, economical political, social and cultural parameters that presuppose the design and performance of architecture, and the real complexity of architecture is the cogent organization and integration of these multivariate parameters, directing its potential effects toward some larger end through an architecture agenda [11].' Moe also emphasized that 'to find the solution for the complexity, morphology of a building's composition should seek to merge architectural intentions with constitutive parameter such as site, climate, energy consumption, materials, and construction [11].' Such integrated design paradigm for performance based design also has lead to changes in

Figure 4. Aqua in Chicago by Jeanne Gang

the role of architects. Moe told that ‘the role of the architect has clearly shifted from individual masters to strategic organizer of manifold, often disparate forms of knowledge and processes. By integrating the design and analysis of buildings around digital technologies of modeling and simulation, the architect’s and engineer’s roles are increasingly being integrated into a relatively seamless digital collaborative enterprise from the earliest, conceptual stages of design [11].’

A performance based approach is a key enabler of rational decision making across many stakeholders and based on a large set of performance criteria [7]. In this new design process, performance measurement with evaluation tools goes hand in hand with a design process providing advice to decision making in every step if the design process. Therefore, a clear understanding of the definition and role of the building simulation as well as the workflow is very important for the success of any performance driven project.

WHAT IS THE BUILDING SIMULATION?

The terminology ‘simulation’ originally comes from the Latin word ‘simulat’ meaning ‘copied, represented’ [12]. Currently ‘building simulation’ generally means to produce a computer model imitating the appearance or physical character of a building for design, evaluation or analysis purpose. The total spectrum of ‘building simulation’ is very wide as it spans energy and mass flow, structural durability, aging, egress, and even construction site simulation. The purpose of simulation is basically to generate observable output states for analysis, and their mapping to suitable quantifications of ‘performance indicators’ [13]. Simulation of building thermal performance using digital computers has been an active area of investigation since the 1960s, with much of the early works focusing on load calculations and energy analysis. Over time, the simulation domain has grown richer and more integrated, with available tools integrating simulation of heat and mass transfer in the building fabric, airflow in the through the building, daylighting, and vast array of system types and components [13]. Augenbroe defined the role of building simulation as following; ‘Building simulation models and observes the building’s behavior under a specific usage scenario. In the simulation, a piece of reality is translated into a model, which is then studied in a variety of experiments (simulation run) in an ‘experiment box’ (the simulation tool). (see figure 5) The experiment is set up to generate observable states that reveal something relevant about the behavior that contributes to the performance under study [7]. To make a simulation successful, a set of clear performance criteria is prerequisite for the experiment. A performance criterion controls the set-up of the experiment and determines the choice of performance quantification. In this point of view, the goal of building simulation expands from performing high fidelity simulation to performing the right type of virtual experiment with the right model/tool, and the building performance simulation can be defined by not just a computational tool but a process including agreement about performance criteria, measuring method to quantify required and fulfilled levels of performance, and making rational design decisions that consider client preferences and optimization in multi-criterion performance targets [7].

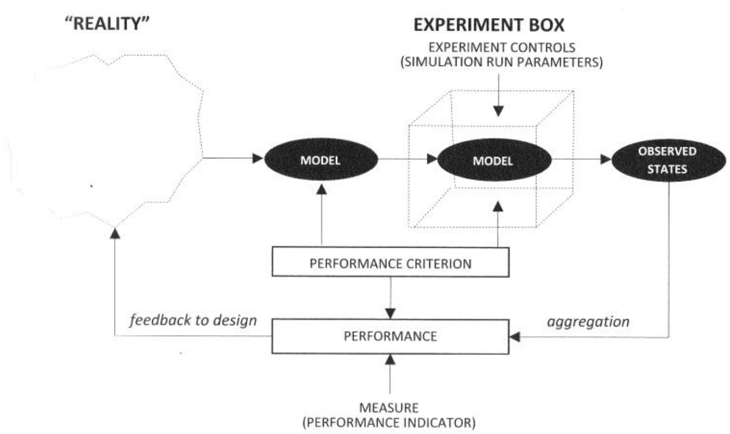


Figure 5. Simulation as virtual experiment by Augenbroe [7]

SIMULATION AND MODELING

Becker and Parker state about the relationship between simulation and modeling that ‘it is common to see the words simulation and modeling used as synonyms, but they are not really the same thing; at least, not to those in the field bearing those words in its name. To be precise in terminology, a simulation enacts, or implements, or instantiates, a model. A model is a description of some system that is to be simulated, and that model is often a mathematical one. A system contains objects of some sort that interact with each other. A model describes the system in such a way that it can be understood by anyone who can read the description and it describes a system at a particular level of abstraction to be used [14].' The energy modeling guideline for architect, An Architect's Guide to Integrating Energy Modeling in the design process' published by AIA in 2012 defines energy modeling as calculation engine that accepts inputs such as building geometry, system characteristics, and operations schedules and produces outputs such as performance comparisons and compliance report. The guideline also classified the energy modeling as 4 types mainly based on the design stages [2];

Design Performance Modeling (DPM) informs design decision by predicting a building's performance with respect to energy efficiency, daylight penetration, glare control, thermal comfort, natural ventilation, and similar factors. It is typically prepared during the early stages of design, before engineering systems are incorporated. Its analysis of energy use is accordingly less complex and time consuming than that of Building Energy Modeling, to allow for more rapid exploration of a greater number of parameters, which may include architectural form impacts, window-to-wall ratio implications, glazing and shading options, R-values of opaque walls, and the like. DPM allows cost, aesthetics, and performance (including energy performance) to be given value and discussed among the project team and with the client in real or almost real time.

Building Energy Modeling (BEM) predicts a building's anticipated energy use and corresponding energy savings, as compared to a standard baseline. In so doing, it demonstrates project compliance with local, regional or national energy codes. BEM predicts energy performance based on Typical Meteorological Year (TMY) data, as well as assumptions about building operation and maintenance. Accordingly, *the prediction is only as accurate as the assumptions*, which should be documented and understood by the project team, as well as the client, the building operator, and the end users. Changes made during the design and construction process should be used to update the BEM, to increase its utility and predictive accuracy.

Building Operation Modeling (BOM) introduces actual utility bills, use patterns, hours of operation, functioning of systems, and real weather conditions for a completed building into a model structured similarly to the Building Energy Model. It thereby allows the comparison
of actual energy use with the predicted use. This comparison can be used to determine causes of discrepancies between predicted energy use and actual energy use, which in turn facilitates tuning of systems to better meet—or even exceed—the design goals. The process of comparison of the BEM and the BOM is known as "calibrated simulation" or Measurement & Verification (M&V). [Presently, there is little industry agreement on a method that accurately compares BEMs to BOMs, accounting for all the potential variations of building use and operations. ASHRAE Guideline 14 and the USDOE's International Performance Measurement & Verification Protocol (IPMVP) provide the currently agreed methods for this type of work.] The Building Operation Model is also used to satisfy emerging building code requirements for post-occupancy monitoring.

Project Resource Modeling (PRM) is the most extensive and broad of the four most common forms of modeling. It assesses multiple resource issues that affect and are affected by the development of a project, including energy, water, material selection, and solid waste. It may also include transportation, primary growth issues, manufacturing, social and agricultural elements, embodied energy, carbon emissions, health, and other factors. This type of extensive study typically addresses the interrelationships among resources, their consumption, efficiencies, and conservation. PRM can assess existing site resources, as well as components that may be brought to the site. It is important to note, in the context of this guide, that energy is only *one* of the resources considered in this broader resource modeling process.

Table 1. Sample US National Average Site EUI

BUILDING TYPE	U.S. NATIONAL AVERAGE SITE EUI
Residential - Single-Family Detached	44
Religious Worship	46
Office - 10,000 sf	74
Education - K-12 School	75
Bank/Financial Institution	77
Health Care - Clinic	84
Office - 10,001 to 100,000 sf	90
Lodging - Hotel/Motel	94
Public Assembly - Entertainment/Culture	95
Office - 100,001 sf or greater	104
Public Assembly - Library	104
Health Care - Hospital Inpatient	227
Food Service - Fast Food	534

The actual energy performance of a building is usually represented as 'energy use intensity (EUI)'. Energy Use Intensity (EUI) is a measurement that describes a building's annual energy consumption relative to the building's gross floor area. To date, this term is most often used as an expression of an existing building's actual, metered energy consumption, or as a comparative average, which is derived from a data set of metered information for a particular building use type in a specific location such as the table 1 showing a sampling of US national average EUI values in $kBtu/ft^2$, as determined by the 2003 Commercial Building Energy Consumption Survey (CBECS). Both of these uses of EUI are based on real, measured building energy use data. EUI can be relative to either site or source energy. Site energy is the measure generally familiar to the design profession. It is the amount of energy consumed by a building and is reflected in utility bills paid by the building owner. Source energy is a more accurate measure of a building's energy footprint, because it includes energy that is lost during production, transmission, and delivery to the building. Electricity is the prime example; what is consumed at the building is only a proportion of the fuel energy fed into the power plant. The simulation results to show the performance of design alternatives, predicted Energy

Use Intensity (pEUI), calculated by the energy model are also usually showed by same metrics, kWh/m^2.yr or kBtu/ft^2.yr. pEUI describes the energy use for a project based on modeled site energy. It is a modeled number; therefore the number hardly matches the actual performance from building operations [2].

BUILDING SIMULATION FOR EARLY DESIGN PHASE

The early stage of building design includes a number of decisions which have a strong influence on the performance throughout the rest of the process [3]. It is therefore important that designers are aware of the consequences of these design decisions. Most of architecture design firms, however, currently don't utilize simulation for energy performance review during the early design phase. Even leading architects that are concerned with environmental factors in their design usually rely on rule of thumb or experiential knowledge from previous project experiences [15]. There is no doubt that, for small-scale project or any simple project allowing reliable performance prediction with rules of thumb or previous experience, it is better not to waste time and cost for unnecessary simulations. Recently, however, the global concern for climate change and energy crisis as well as raised expectation of indoor environment quality for occupants require not just to meet the minimum code requirement but to provide a high performance building that is stimulating, healing or relaxing as well as guarantee significant reduction in energy demand. Moreover, in the complicated contemporary design process concerning multiple performance criteria such as daylighting, energy demand, natural ventilation, thermal comfort, visual comfort and concurrent multi parameter, decision making (walls, windows, ceiling, floor, shading, finish materials, lightings etc) can not be supported by simple rules of thumb or personal experiences, but requires carefully designed performance criteria and their evaluations. Only by doing so, we can offer reliable performance guarantees for the final project [5].

Considering the schematic design phase and its inherent lack of detailed information, the most prevalent simulation tools are not suitable to apply in this early design phase [41]. Many researches in the academic and professional fields are devoting efforts to develop simulation method which can be efficiently integrated in the design process and provide the information that is relevant to design decisions. To understand the specific requirement for simulation as information provider during the early design phase, it is helpful to clarify the general architecture design process based going through different design phases.

Architecture Design Phases

The architecture design process can be defined as several phases, and each phase has a specific work scope and target. There are several ways to divide the phases, but the American Institute of Architects (AIA) officially define the architect's basic services as 5 phases; schematic design, design development, construction document, bid or negotiation, and construction administration [16].

<u>Schematic Design Phase</u>:

It is the first phase of architecture design process, and is regarded as the early design phase. During the phase architect consults with the owner to determine project goals and requirements. Often this determines the program for the project. The program, or architectural program, is the term used to define the required functions of the project. It should include estimated square footage of each usage type and any other elements that achieve the project goals. The project team also decides the performance criteria based on the project requirement and design strategy to fulfill the performance targets. During schematic design, an architect commonly develops study drawings, documents, or other media that illustrate the concepts of the design and include spatial relationships, scale, and form for the owner to review. Schematic design is the research phase of the project, when zoning requirements or jurisdictional restrictions are discovered and addressed. Because of that architects usually generate various design alternatives and compare them to make best decision to fulfill the project goal during this phase. This phase produces a final schematic design, to which the owner agrees after consultation and discussions with the architect. Costs are estimated based on overall project volume. The design then moves forward to the design development phase.

Design Development Phase:

Design development (DD) services use the initial design documents from the schematic phase and take them one step further. This phase lays out mechanical, electrical, plumbing, structural, and architectural details. This phase results in drawings that often specify design elements such as material types and location of windows and doors. The level of detail provided in the DD phase is determined by the owner's request and the project requirements. The DD phase often ends with a formal presentation to, and approval by, the owner.

Construction Document Phase:

Once the owner and architect are satisfied with the documents produced during DD, the architect moves forward, and produce drawings with greater detail. These drawings typically include specifications for construction details and materials. Once CDs are satisfactorily produced, the architect sends them to contractors for pricing or bidding, if part of the contract. The level of detail in CDs may vary depending on the owner's preference. If the CD set is not 100-percent complete, this is noted on the CD set when it is sent out for bid. This phase results in the contractors' final estimate of project costs.

Bid or Negotiation Phase:

The first step of this phase is preparation of the bid documents to go out to potential contractors for pricing. The bid document set often includes an advertisement for bids, instructions to bidders, the bid form, bid documents, the owner-contractor agreement, labor and material payment bond, and any other sections necessary for successful price bids. For some projects that have unique aspects or complex requirements, the architect and owner elect to have a prebid meeting for potential contractors. After bid sets are distributed, both the owner and architect wait for bids to come in. The owner, with the help of the architect, evaluates the bids and selects a winning bid. Any negotiation with the bidder of price or project scope, if necessary, should be done before the contract for construction is signed. The final step is to award the contract to the selected bidder with a formal letter of intent to allow construction to begin.

Construction Administration Phase:

Contract administration (CA) services are rendered at the owner's discretion and are outlined in the owner-architect construction agreement. Different owner-architect-contractor agreements require different levels of services on the architect's part. CA services begin with the initial contract for construction and terminate when the final certificate of payment is issued. The architect's core responsibility during this phase is to help the contractor to build the project as specified in the CDs as approved by the owner. Questions may arise on site that requires the architect to develop architectural sketches: drawings issued after construction documents have been released that offer additional clarification to finish the project properly. Different situations may require the architect to issue a Change in Services to complete the project.

Simulation Demand during Early Design Phase

Sustainability is not only high performance materials or mechanical equipment but also innovative design strategies regarding daylighting, energy saving, natural ventilation, solar control, and building integrated renewable energy systems. Good examples can be found in many recent examples of experimental architecture that explore new frontiers in building technology. Those ideas are usually introduced with fabulously looking diagrams or fancy colorful simulation images, and visually represented in actual building which is usually announced as state of the art green building with a proclaimed extremely low energy demand. (see figure 6) The buildings advertised as super innovative green design come however with high initial cost. What is worse, many times there is a huge gap between the actual performance and the promised design performances, and many unexpected problems show up after the building has been occupied. The reason can often be found in the design process when a quantitative validation regarding expected performance or design review based on reliable domain knowledge was missing. This poses a substantial risk factor to fail the required function or performance of the building. Implicit trust for simulation result without clear understanding about the process and their limitation can also cause various problems with too much optimistic expectation for actual performance. Therefore, the quantitative validation for performance with proper simulation tool for each design stage should be executed with clear performance target, reliable domain knowledge, and sufficient understanding for simulation tools throughout the design process. Especially in early design phase, rational simulation tool selection and

Figure 6. Pearl River Tower, Guangzhow, China

the way how to integrate it into design process is very critical to complete the project successfully.

The Integration of Building Performance Analysis with Design Process

Since the analysis of building performance became the important factor in design decision making [18], there have been many concerns that how to aid for designers to get information for building performance effectively especially during early design phase. Recently AIA published 'An Architect's Guide to Integrating Energy Modeling in Design Process' which introduce the process, parameters and various tools of energy modeling, and it shows that architects now begin to understand that energy analysis is not the expert knowledge only for some engineers but mandatory professional knowledge for all architects. The development of energy simulation tools applicable for the early design phase is very limited, and the tools designed for non-expert users without domain knowledge and experience give no reason to expect a benefit in application for real projects [13].

Architects expect tools which can aid understanding the relationship between design factors and building performance. Moreover, clearly distinctive perspective between architects and engineers for design thinking and expectation regarding simulation tools [20] increases the demand for tools which can be coupled with the design process effectively. The architecture software industry slowly shows their interest in this market. The market focus is to improve design process efficiency with convenient information exchange between design tools and energy analysis tools, which allow to simultaneously check the relationship between design factors and performance. Even though there are still major limitations, there are several tools developed for architects as their main target users. OpenStudio is developed by the National Renewable Energy Laboratory, and it is an interface that provides users easy access to a number of building analysis engines such as EnergyPlus, Radiance, and Contam. OpenStudio includes a SketchUp-type modeling capability that allows users to build geometry, space types, and thermal and lighting zones in a 3D modeling construct which is very familiar to general architects. This program is freeware and open-source and people can download the program via website http://openstudio.nrel.gov.

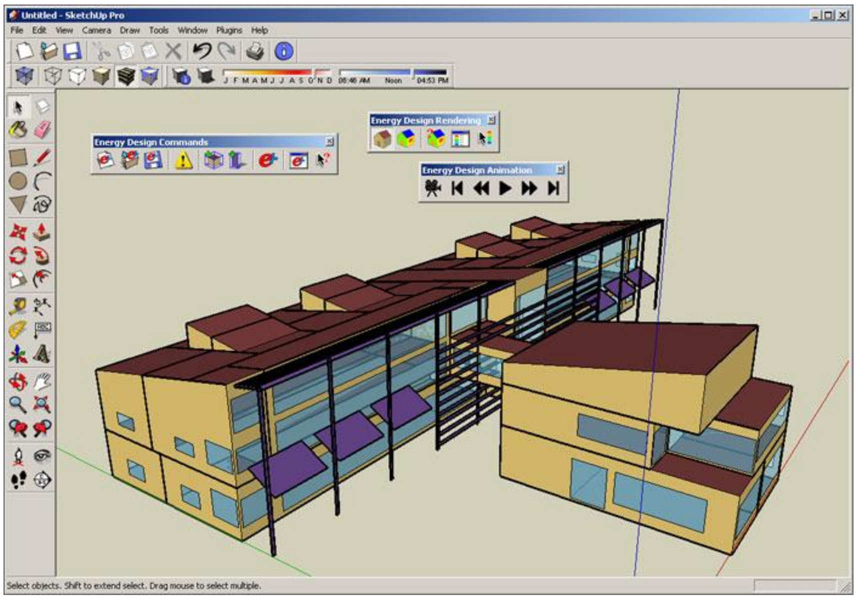


Figure 7. OpenStudio with SketchUp

ECOTECT, one of the most popular assessment tools for architects as well as engineers, has a user friendly GUI, and it provides quick, early, iterative type of energy modeling, especially for daylighting [22]. The weather data information and graphic results regarding solar analysis are powerful and attractive even though it has some severe limitation as ‘black box’ in energy simulations. The daylighting simulation is reliable especially when it is coupled with the simulation engine ‘Radiance’[21], and 3D models generated by other graphic programs such as SketchUp, Rhino, AutoCad, and Revit can be easily imported into ECOTECT with DXF, XML, 3DS or IFC file format. The program was originally developed by Square One, and it was sold by the architecture software giant, Autodesk, in 2008.

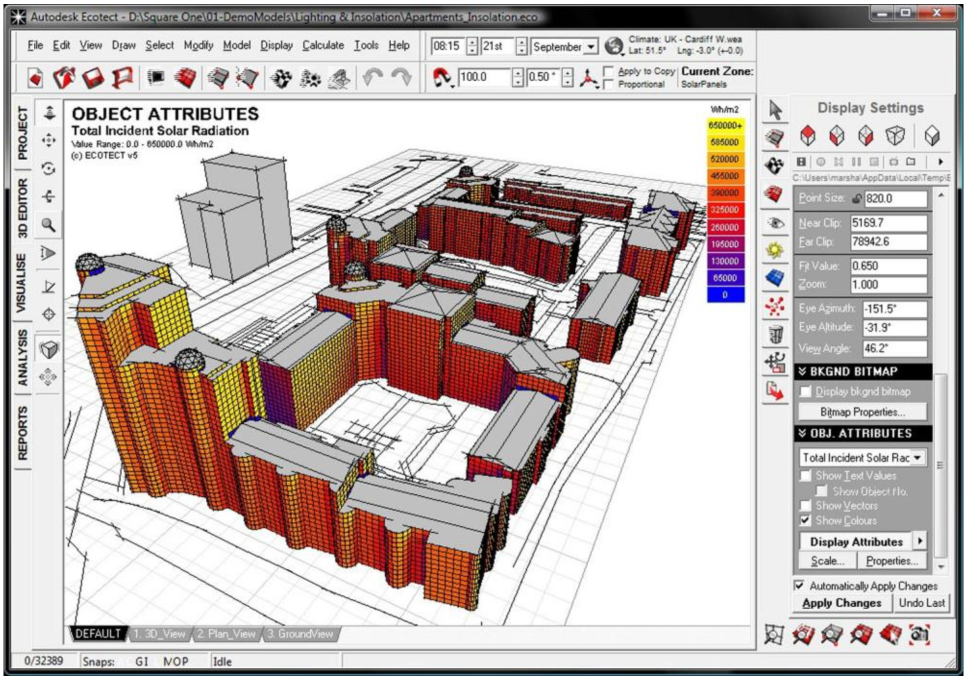


Figure 8. ECOTECT

Another simulation tool developed for architects by Autodesk is Green Building Studio (GBS). This is web based service using DOE-2.2 simulation engine to provide energy, water, daylighting, and carbon analysis based on building information model (BIM) and certain 3D CAD building designs. The newest generation of GBS is Project Vasari, which combines with ECOTECT to provide building energy modeling specifically geared to early design. This cloud-based service provides simple, automatically generated models and large-capacity computing power with cloud computing resources to manipulate a variety of parameters and get results quickly [22]. However, this program has inherent reliability problem because it is challenging to track where energy-saving results are coming from and what building or system components are influencing those savings. It also can't provide sufficient service for detailed manipulation of building components after the early design phase. Although it is not easy to find solutions for those issues, it can grow out to become a positive business model for energy simulation in the architectural office in near future.

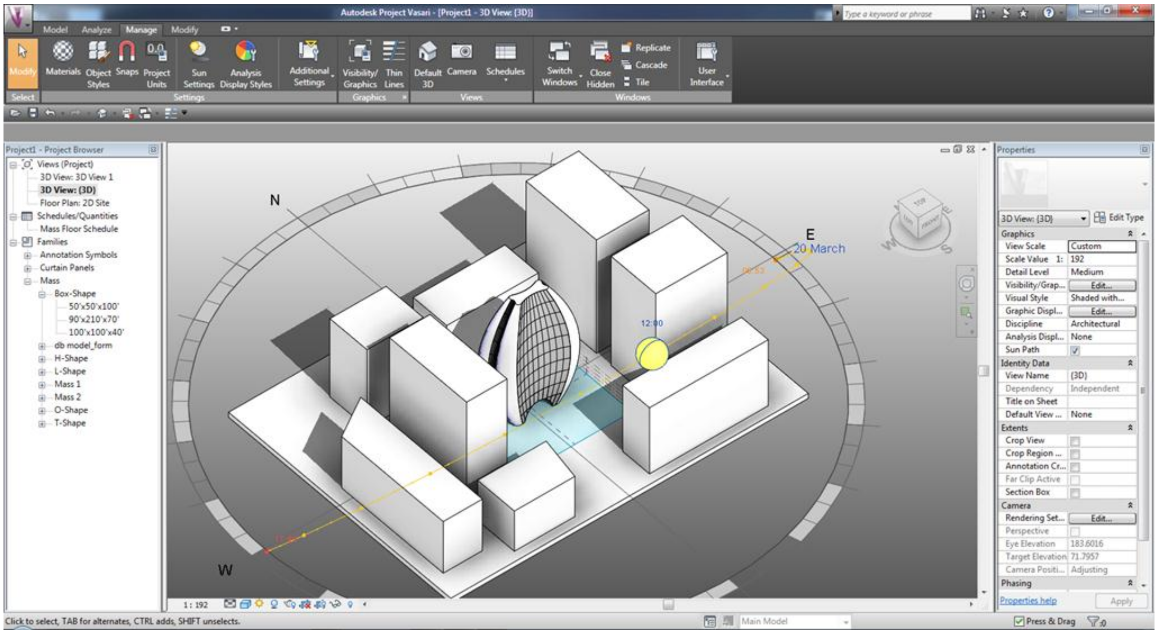


Figure 9. Vasary by Autodesk

Besides of those tools, many plug-ins for energy simulation engines, such as EnergyPlus, Radiance, which can run in existing 3D design tools such as Rhino and SketchUp are also actively developed. The plug-ins can provide benefits for designers to apply simulation tools without extra time and labors, and get instant feedback for performance regarding their design parameter changes. As mentioned above, however, even the tools developed for architects cannot be applied effectively without general understanding for simulation and knowledge about building physics, and the integrated collaboration with the expert energy consultant is crucial for the success of the project throughout the entire design phases.

Augenbroe defined the design-integrated tool types in his book 'Advanced building simulation' as 4 ways based on interoperability of shared information between design team and domain experts, communication between working groups, and their workflow [13]. (see figure 10) The ways of design integration can be more enhanced by internet-based infrastructure such as cloud computing environments. In the new

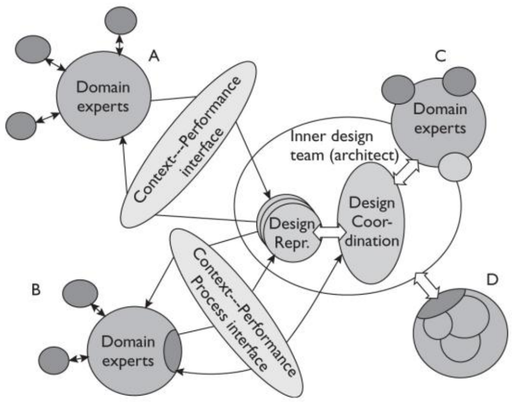


Figure 10. variants of delegation of expert analysis to domain experts and their tools [13]

ecosystem, the role of architects should be expanded from traditional design oriented professional to design process coordination. Proper coordination requires a dynamic view of all design activities, verification of their interrelatedness and anticipation of expected downstream impacts of alternative decisions [13]. The multidisciplinary perspective and information analysis can contribute to optimized design decision combined aesthetic design and the required performance. To support the collaboration we need the fundamental mutual understandings of the process among architects, engineers and researchers.

Parametric solutions for energy modeling in early design phase

During the early design phase, we need to compare alternatives or sometimes find optimal component properties. This can lead to a cumbersome job given the lack of interoperability between design and simulation tools when applied repetitively in an iterative design process. Specifying inputs, such as building geometry, floor area, glazing area, volume, and ceiling height, for every design alternative is a job which needs extra time and labor. Quickly comparing various alternatives along pre-defined criteria is greatly enhanced by, the integration of parametric modeling and simulation in a common interface. Moreover, the integration can inform the sensitivity regarding various performances in responding to the design parameter changes as real time. The sensitivity study will for instance provide important information to determine a heuristic methodology for daylighting design in early design stage. Our case study uses the

Grasshopper tool for parametric modeling. It has powerful expandability with external plug-ins, and also introduces several attractive building simulation related plug-ins.

Grasshopper

Grasshopper® is a graphical algorithm editor tightly integrated with Rhino's 3-D modeling tools developed by David Rutten at Robert McNeel & Associates. Unlike RhinoScript based on VB script, Grasshopper requires no knowledge of programming or scripting. Grasshopper as a script-based modeling offers the designer new way to specify their design, as well as new way to control the design process; procedure automation, geometry definition through mathematical functions, parametric model generation which allows large and quick changes in the initial geometry of the model, the ability to quickly obtain complex shapes through reiterated geometrical elements. The script based modeling tool also provides additional benefit in using mathematical functions for building physics. It allows applying various analysis and optimization tools for building performance such as structure, daylighting, and energy calculations [23].

DIVA

DIVA-for-Rhino is a highly optimized daylighting and energy modeling plug-in for the Rhinoceros - NURBS modeler. The plug-in was initially developed at the Graduate School of Design at Harvard University and is now distributed and developed by Solemma LLC. Because this plug in is developed by architect, light engineer, building scientist, and academic advisor as one team, it understand the various needs from different user types. This software is using simulation engine with Radiance and Daysim for solar, and EnergyPlus for thermal. DIVA-for-Rhino allows users to carry out a series of environmental performance evaluations of individual buildings and urban landscapes including Radiation Maps, Photorealistic Renderings, Climate-Based Daylighting

Metrics, Annual and Individual Time Step Glare Analysis, LEED and CHPS Daylighting Compliance, and Single Thermal Zone Energy and Load Calculations [24].

Ladybug

Ladybug is a free and open source environmental plugin for Grasshopper to help designers create an environmentally-conscious architectural design. The initial step in the design process should be the weather data analysis; a thorough understanding of the weather data will, more likely, lead designers to high-performance design decisions. Ladybug imports standard EnergyPlus Weather files (.EPW) in Grasshopper and provides a variety of 2D and 3D designer-friendly interactive graphics to support the decision-making process during the initial stages of design. The tool also provides further support for designers to test their initial design options for implications from radiation and sunlight-hours analyses results. Integration with Grasshopper allows for an almost instantaneous feedback on design modifications, and as it runs within the design environment, the information and analysis is interactive [25].

Kangaroo

Kangaroo is an add-on for Grasshopper/Rhino and Generative Components which embeds physical behavior directly in the 3D modeling environment and allows user to interact with it 'live' as the simulation is running. It can be used for various sorts of optimization, structural analysis, animation and more [25].

GECO

GECO developed by Uto offers a direct link between Rhino/Grasshopper models and Ecotect. The Plug-in allows users to export complex geometries very quickly, evaluate their designs in Ecotect and access the performances data, to import the results as feedback to Grasshopper. This could be done as single process or loop to improve performance and the design of a building in the context of its environment. The single results of the process could be saved inside Rhino in the vertices of the analysis mesh to store data for later use inside different design approaches [26].

INTEGRATED DESIGN WORKFLOW IN PARAMETRIC MODELING PLATFORM

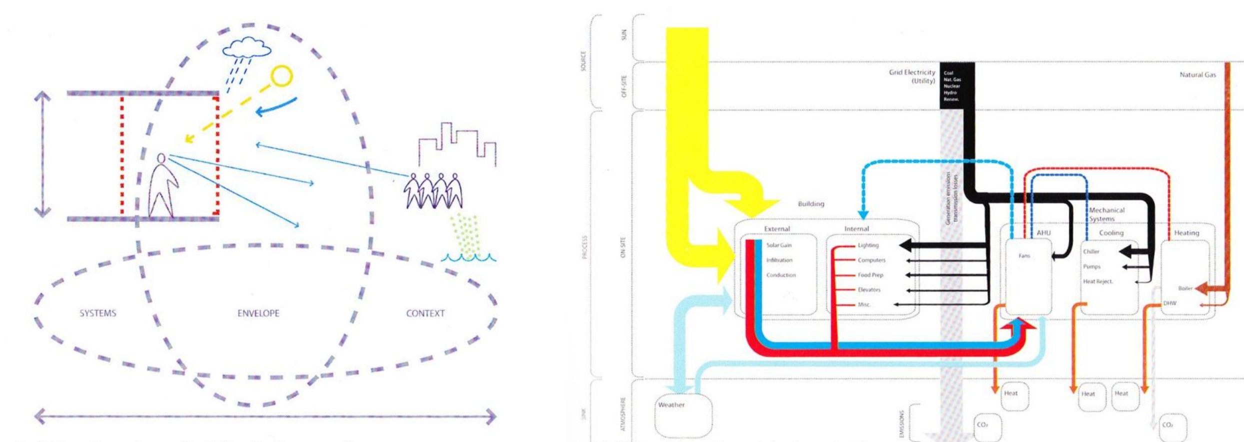
This thesis introduces integrated design workflow utilizing a parametric modeling platform and convenient simulation tools which can be linked to the platform directly or indirectly. The purpose is the instant performance feedback by design parameter variation using parametric modeling platform. Because the parametric modeling tool can generate various design alternatives very easily with simple parameter variation, the complicated and time/labor consuming performance verification process with various design alternatives in conventional design workflow can be dramatically improved with saving in time and labor. The whole process can be classified as 3 major steps: Initialization, Integrated design with parametric modeling, and Decision making.

Initialization

It is very important for the building design to satisfy the required performance without compromising or deteriorating the aesthetical design quality. To achieve the goal with balance needs a clear design direction and iterative design verification. It helps to find problems that need to be solved in the project, and guides the design team to understand necessary condition to find right design solution. Therefore to declare performance criteria and their targets is not just a functional and engineering issue but a design issue as well.

It needs close communication between client and design team to define what performance criteria should be included and what the design target should be. Client should provide clear expectations for the building as well as relevant information regarding the project including available project budget. The design team should provide design intent as well as basic system concept based on the client expectation. Ideally the design team should consist of designers as well as engineers from the early design phase, but in case only designers (architects) are leading the design, they should have relevant domain knowledge regarding building physics and systems to understand the basic system concept and effectively communicate and coordinate with outside consultants. Because buildings with same use and functions can have different problems depending on their site context and climate condition, the local environment should become important factor to define the performance criteria and their goals.

Integrated Design with Parametric modeling



Building Facade as Architect's Perspective

Building Facade as Engineer's Perspective

Figure 11. Conflicting Perspective regarding Building Façade

After the performance criteria and their goals are defined, design solutions are explored to fulfill the requirements. As the professional perspectives by architects and engineers to building envelopes are quite different (see figure 11) [1], a parallel design approach for building and system needs to be enforced. With the initial design concept based on design intent and empirical knowledge, the first step to develop the design process is to analyze the functional systems of the building for understanding the relationship between client expectations (demand) and their solutions (system) as well as finding relevant design parameters to control the match between expectation and fulfillment. This thesis uses the methodology proposed by Augenbroe; Top-down functional decomposition and bottom-up assembly of building system [7]. The system analysis process helps to rationalize the relationship between building functional requirements and systems to fulfill their technical solutions, which makes available to design parametric modeling code considering both design intent and functional system performance with proper parameter set up. It also defines proper performance indicators to check the required performance as well as the simulation methods.

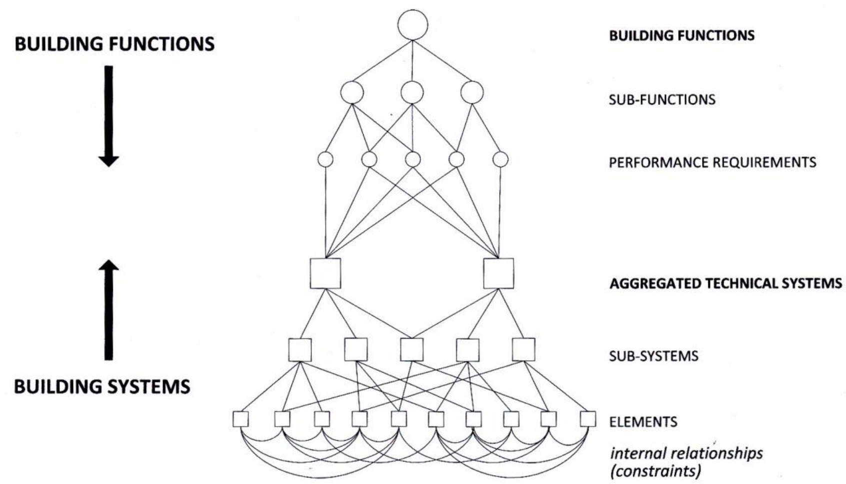


Figure 12. Functional decomposition and bottom up building system

The parametric design platform provides two major roles in design and performance. The first role is to generate design alternatives with parameter variation and design intent. Parameter change such as window size, window bay size, louver angle, height, light shelf depth, wall geometry, and material properties can be changed within certain ranges to check the performance changes. The parametric modeling is the best platform to generate alternatives, but it should be kept in mind that the modeling code should be defined to make sure that it is capable to distinguish performance for different design variations. The other role is to link the simulation program with building geometry. Instant feedback of ‘performance indicator’ value leads to an understanding the relationship between design parameter and their performance effects. Updating the design parameter to meet the performance goal in the iterative design loop will be used to determine an optimized or most acceptable solution. The architect should obviously review whether the design also meets all other original design intents at every step; otherwise it is easy to lose the balance between design concept and their performance.

Decision Making

The final design is made by comparing performance indicators for each design alternatives. Because each PI value has different metrics, the values should be normalized into the same scale to be fairly compared. If this is not feasible, different PI's can be weighted with different value depending on the hierarchy of importance in the project goal, which can be defined by client and design team together. Radar charts are convenient to compare multiple performance criteria. After the design is selected it is further developed with material selection and construction details. Various other PI's such as Life Cycle Assessment, cost, constructability, and maintenance can be taken along in the design decision in each phase.

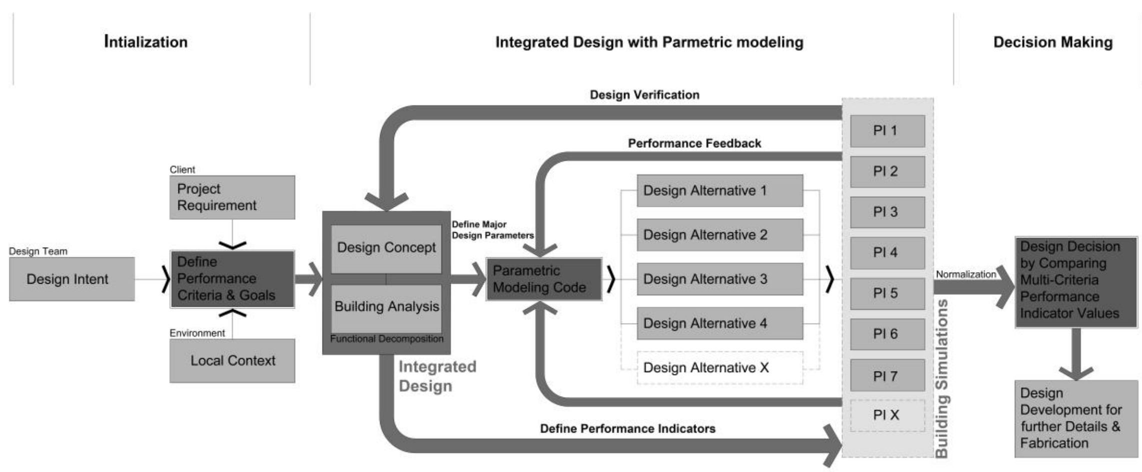


Figure 13. Integrated workflow for facade design with parametric modeling

CHAPTER 3

CASE STUDY FOR HIGH PERFORMANCE FAÇADE DESIGN

PROJECT DESCRIPTION

This chapter presents the case study to test the performance based design approach, i.e. a particular office building design process with integrated performance analysis. The target is an integrated design process for a high performance facade based on a parametric design tool linked with several building analysis tools. The building analysis tools are all freeware or freeware version for students and the design is limited to early phase schematic design, comparing alternatives and deciding the best scheme.

The façade design is for a small scale office building which is located in Seoul, Korea. The office building is currently under design by a Korean architect and the façade design is part of the project. Even though the 6 story office building is small scale about 950m2 for gross floor area, the client wants to put an impressive green accent on this building façade especially with respect to actual performance not just as aesthetical expression of a green wall. Because the site is located on one of the commercially hottest spot in Seoul, Chungdam-Dong, the building needs to bring visual attraction as well. Therefore, how the façade design can accomplish prominent energy saving without compromising aesthetical value is the big challenge for this project.

SITE ANALYSIS

General Condition

Figure 14. Site Map

The project site is Seoul, Korea which geographical location 37°N in latitude and 127° 30′E in longitude. The exact site address is 97-14 Chungdam-Dong, Gangnam-Gu, Seoul, Korea. Gangnam is very interesting district as the core place for commercial, entertainment and culture in Seoul. This district is also famous for most expensive residential area in South Korea. Chungdam-Dong is the central town leading fashion, entertainment, commercial, and culture even in Gangnam, which is usually called Beverly Hills in Seoul. A lot of brand shops such as Chanel, Louis Vuitton, Pradas are around the town with fancy restaurants and galleries. Most of famous firms for entertainment business related to movie or K-Pops have offices in the district. This area used to be residential area with small private houses, and it has rapidly transformed to commercial district since about 10 years before, which raised real estate value incredibly and most of the existing houses are rebuild to commercial buildings for better profit.

Neighbor Environment

The site is located one block behind of 40m Main Street of the district, Dosan-Daero. The site, 18m wide on east to west and 12m depth on north to south, is facing two street at north and west which is 12m and 8m each. On east side there is adjacent building, 15m high, with just minimum distance set-back by code, 0.5m, and there is also 3story high

(12m) neighbor building next to south property line, which cause some shade to the site. Currently new construction for 20 story high office building is undergoing on the next of south neighbor building, and it will affect in solar access and view to the direction in some degree. The site is on the hill with about 15% degree slope down from west to east. As the central commercial area, there is some noise issue which needs to be considered during design. North and west is the main direction for both view to outside and public vista from street to this building.

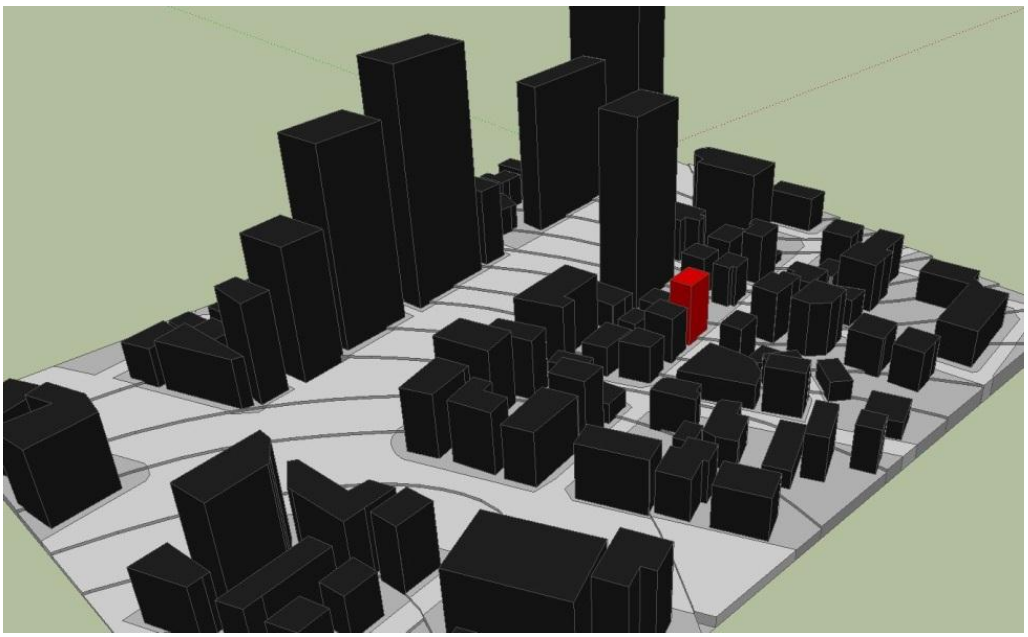


Figure 15. Site 3D model by SketchUp

Climate

General Description

Seoul has a humid continental/subtropical transitional climate with characteristics of both. Summers are generally hot and humid, with the East Asian monsoon taking place from June until July. August, the warmest month, has an average temperature of 22.4 to 29.6 °C (72 to 85 °F) with higher temperatures possible. Winters are often relatively cold with an average January temperature of -5.9 to 1.5 °C (21.4 to 34.7 °F) and are generally much drier than summers, with an average of 28 days of snow annually.

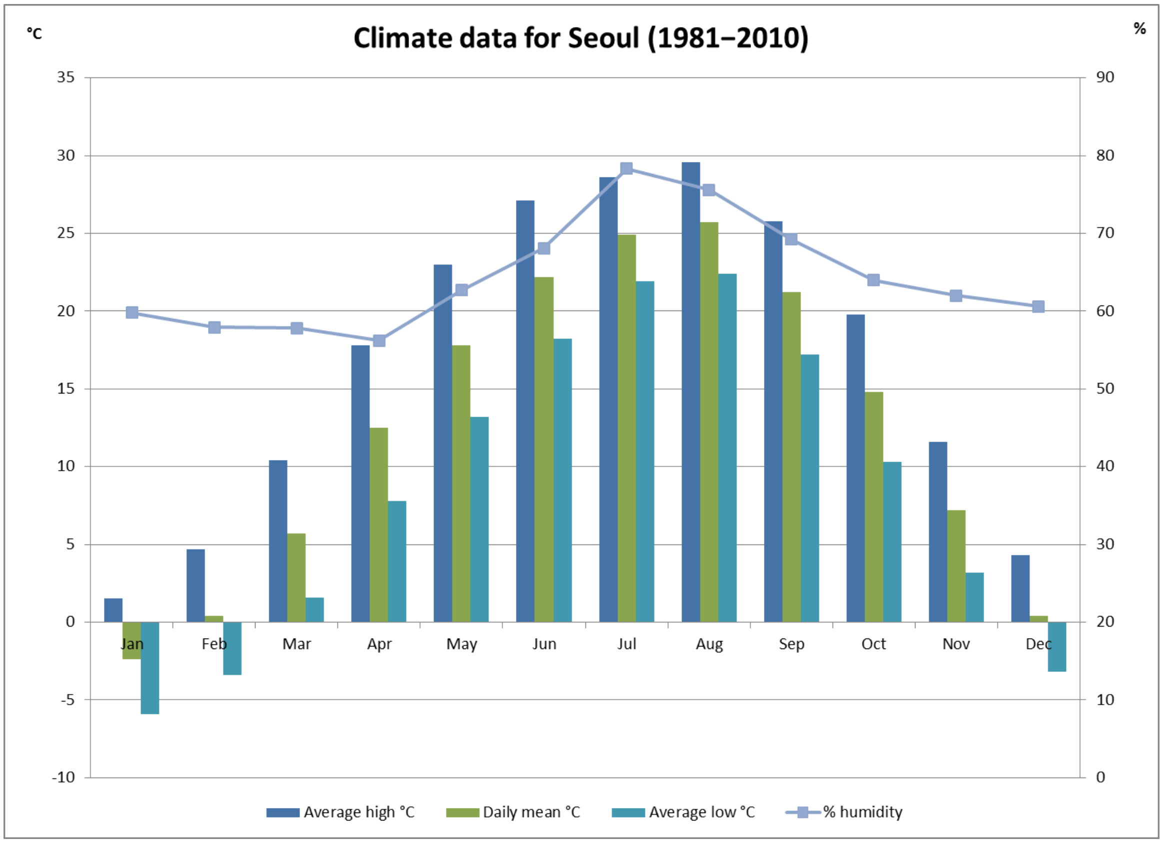


Figure 16. Climate data for Seoul

<u>Solar Condition</u>

The site has some limited solar access on south and east side. Because of the adjacent buildings and the 20-story new construction, the south façade on lower floor has relatively low solar radiation throughout the year. With the demolition of the existing west building which is part of the new construction, the west façade is the most exposed to solar radiation which can be a benefit for heating during winter, but can be extra heat gain to increase cooling load during summer. The west façade solar access can be also negative impact for visual comfort with glare problem. Figure 17 shows the solar analysis for annual radiation by Ecotect around site area.

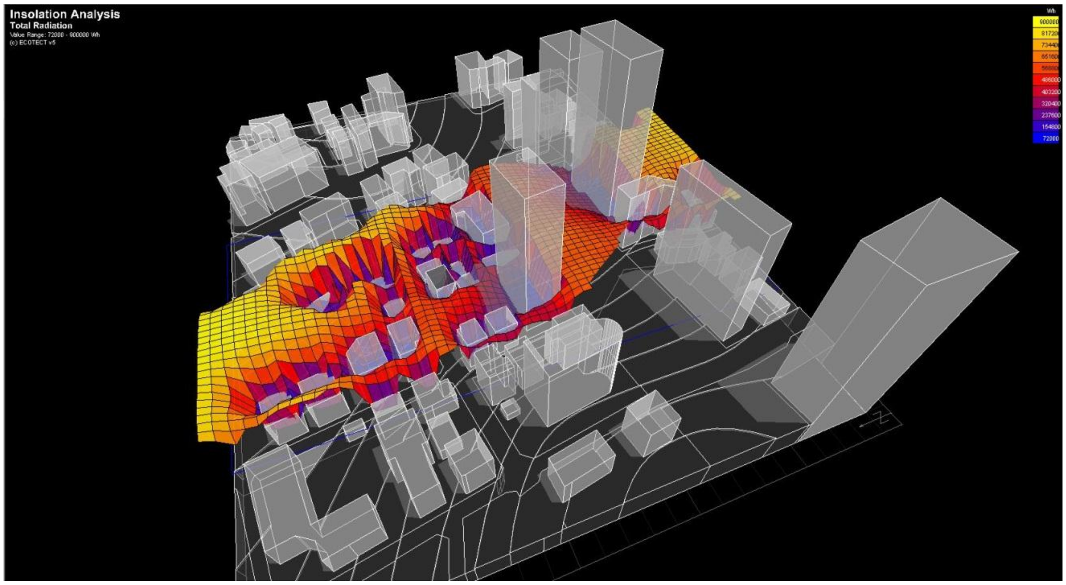


Figure 17. Site solar irradiance simulation by ECOTECT

The annual solar radiation amount on the building surfaces is also examined. The expected volume of the building was added on site for the lighting simulation, and the simulation was done with the Rhino 3D interface with DIVA plug in. The image clearly shows that west and north faces have more exposure on solar radiation throughout the year.

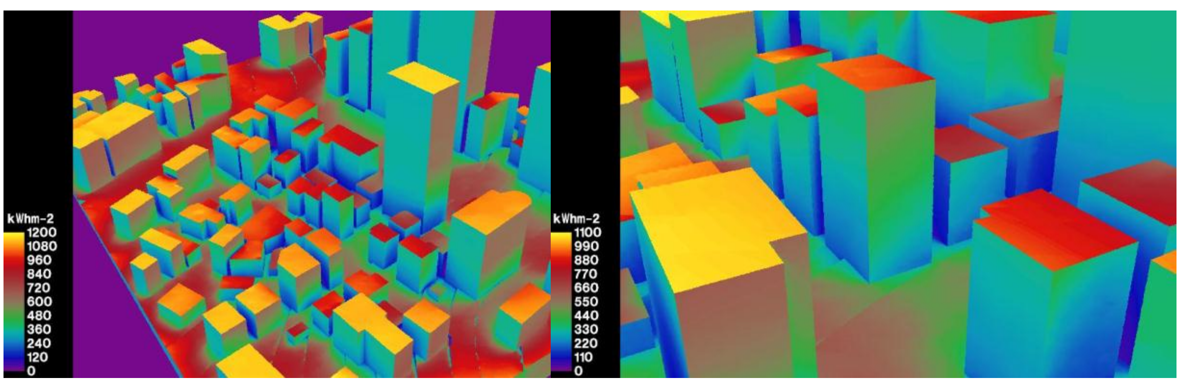


Figure 18. Building facade solar irradiance analysis by DIVA

A shadow study was also done by Ecotect to check how surrounding buildings effect on site area. Because the site is densely surrounded by other buildings and the site area is too small to preserve extra space for solar benefit, especially in south façade at lower levels will be shaded for relatively long periods during the year. By local regulation the building area will occupy 50% of the site. To minimize the shade impact on the south façade the building will be placed along north perimeter of the site to reserve maximum distance to southern neighbor building.

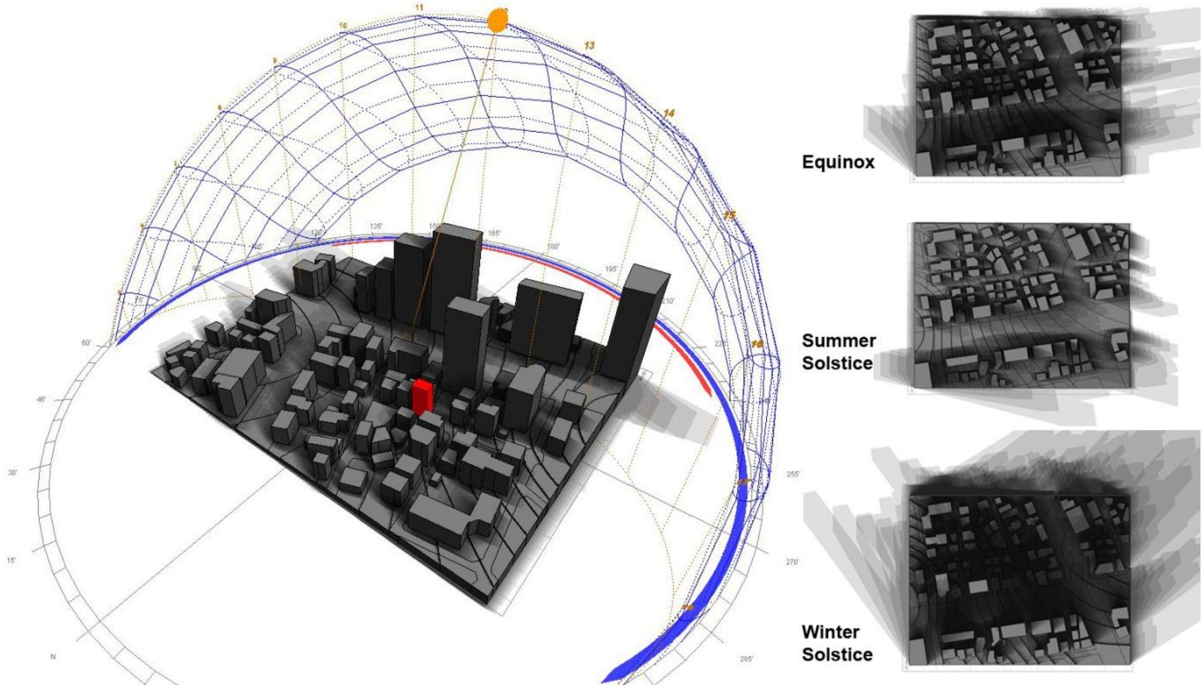


Figure 19. Site shadow study by ECOTECT

Wind Condition

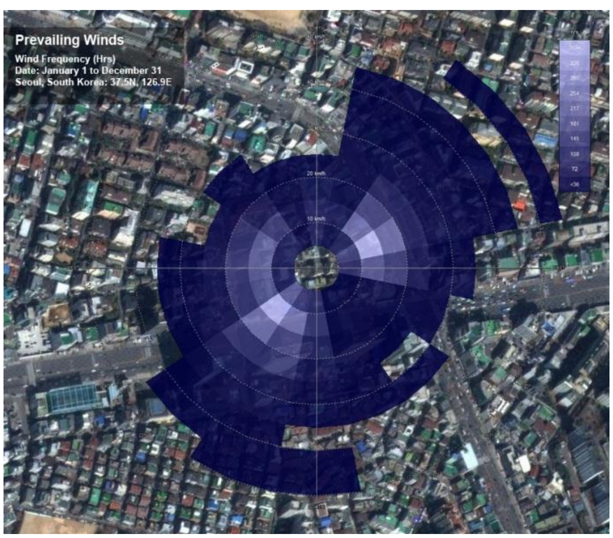


Figure 20. Wind condition on site area

As Seoul located on 37°N in latitude surrounded with ocean on east, west and south, the prevailing wind during summer is from south west direction, and during winter is from north-west direction. The wind analysis on site is shown on the figure 21. Even though prevailing wind direction is relatively stable throughout a year, the intensity is shifting season by season. As seen below, spring and summer has more wind, and the fall season is relatively less. Over the course of the year typical wind speeds vary from 0 mph to 14 mph (calm to moderate breeze), rarely exceeding 20 mph (fresh breeze). The *highest* average wind speed of 7 mph (light breeze) occurs around April 27, at which time the average daily maximum wind speed is 14 mph (moderate breeze). The *lowest* average wind speed of 5 mph (light breeze) occurs around October 2, at which time the average daily maximum wind speed is 10 mph (gentle breeze).

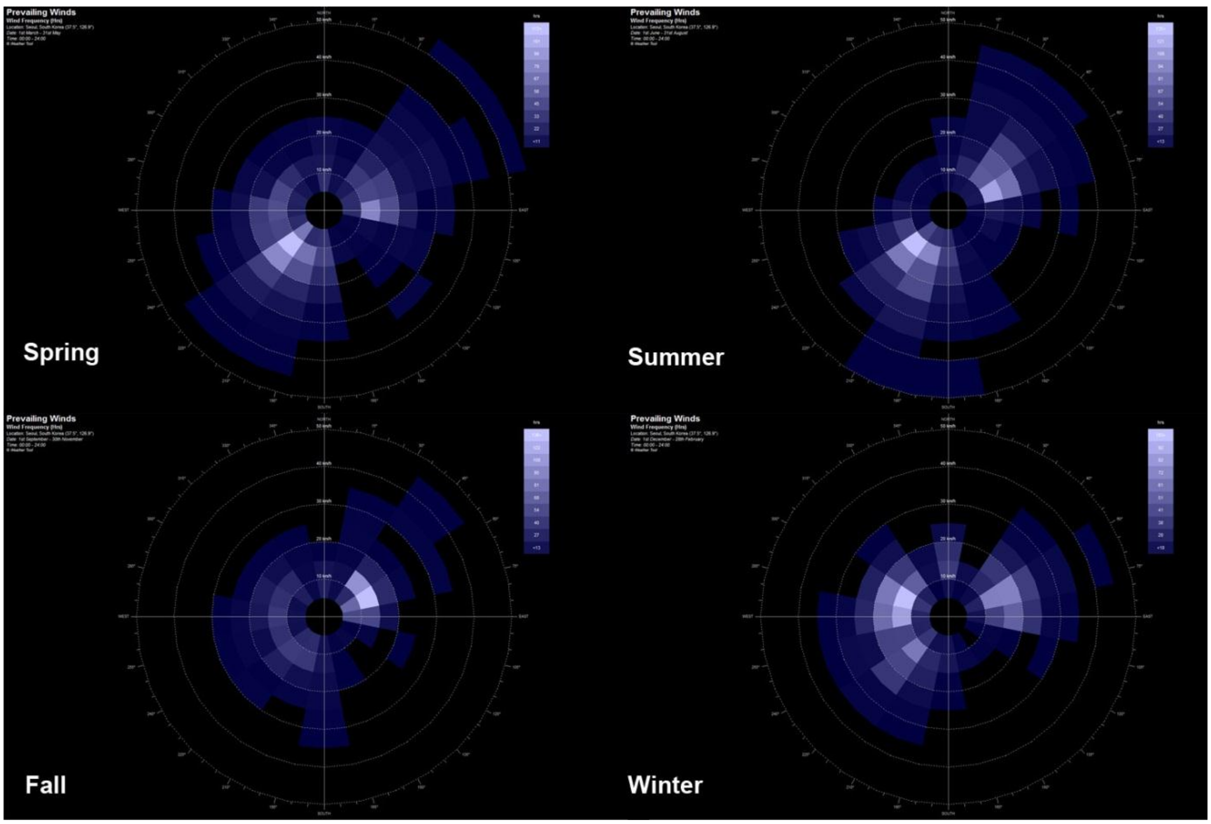


Figure 21. Annual wind condition by seasons

PROJECT REQUIREMENT

It is always very important to have clear design direction in the early design phase especially for performance based design. To define the requirements for the façade design, the design team and owner should discuss the design goal and the relevant performance criteria. Rather than general and subjective design goal such as sustainable design building, the project requirement has to be more specific and objective to find proper design strategy. The team also had to define the performance indicators to objectively compare alternatives for each performance criterion. In terms of building performance, owner and design team agreed on the following performance criteria;

1) Visual Transparency: The occupants should have visual connection with outside environments to maximize spatial openness to compensate for the limited floor area.
2) Proper Daylighting Level: The façade design should bring comfortable and productive indoor lighting environment with daylighting.
3) Minimum Energy Demand: The façade should be designed for minimum heating and cooling demand for energy efficiency.
4) Natural Ventilation: The design should consider the natural ventilation for physical/psychological connection with outside environment as well as healthy indoor air quality.
5) Minimum Environmental Impact: For fabrication level, materials need to be considered with embodied energy and carbon footprints in Life Cycle Assessment.

SYSTEM FRAMEWORK FOR HIGH PERFORMANCE FAÇADE DESIGN

The multiple-performance criteria listed above have trade-off relationships in actual building. For example, to increase window size for more daylighting can result in more energy cost by increased cooling demand. The natural ventilation can also raise the heating or cooling demand depending on the outdoor air temperature. Therefore, the clear understanding of the relationships between design parameters of technical systems and their functions for dedicated performance requirement should be analyzed to before starting the generation of designs that satisfy the multiple-performance targets. As introduced in the book chapter in ‘Building Performance Simulation for Design and Operation’ by Augenbroe, a main function of building can be decomposed into lower level functions [7]. During this decomposition one will arrive at functional criteria that can be expressed as explicit performance requirements. Performance requirements are measured by performance indicators (PIs) quantifiable indicators that adequately represent a particular performance requirement. Each performance requirement is supported by aggregated technical systems which are also decomposed to subsystems and building elements which parameters need to be defined through design process to fulfill the functional requirement [7].

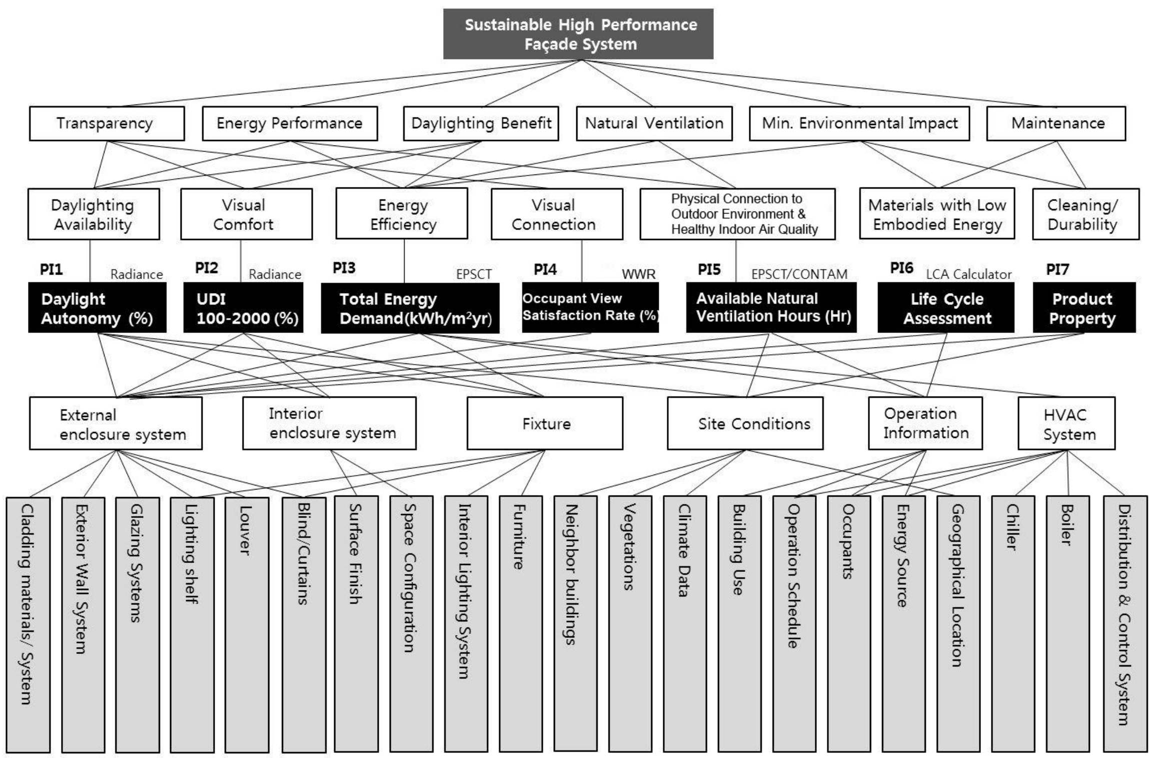


Figure 22. Functional system analysis for High performance façade system. Original diagram format: Augenbroe (2010) [7]

As seen on the figure 22, the high performance façade system is decomposed to sub-functions and their requirements supported by building systems. The functional requirements are measured by following metrics.

Daylight Autonomy

Daylight Autonomy (DA), uses workplane illuminance as an indicator of whether there is sufficient daylight in a space so that an occupant can work by daylight alone. Reference value for minimum illuminance level can be taken from documents such as IESNA Lighting Handbook. It is measured as percentage (%) of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone. In this project, the minimum lighting level is 500lx referred by IESNA Lighting Handbook for office building [29].

Useful Daylight Index

This relatively new metrics was proposed by Mardaljevic & Nabil in 2005. UDI is founded on an annual time-series of absolute values for illuminance predicted under realistic skies generated from standard meteorological datasets. Achieved UDI is defined as the annual occurrence of illuminances across the work plane where all the illuminances are within the range from 100 to 2000 lux. The degree to which UDI is not achieved because illuminances exceed the upper limit is indicative of the potential for occupant discomfort such as glare [30].

Energy Use Intensity

EUI is a measurement that describes a building’s annual energy consumption relative to the building’s gross floor area. (kWh/m^2.yr) This term is most often used as an expression of an existing building’s actual, metered energy consumption, or as a comparative average, benchmark, which is derived from a data set of normatively analyzed buildings of the same type in same location.

Occupant View Satisfaction Rate

Providing access to views of the outdoors, through the incorporation of vision glazing, enables building occupants to maintain a visual connection to the surrounding environment. A survey of 139 office workers regarding the importance of view shows that over 90% of respondents in windowless spaces expressed dissatisfaction with the lack of windows. People complained about the windowless offices for the reasons such as no daylight, poor ventilation, lack of information about the weather, lack of view, feeling of isolation and feeling of depression and tension [44]. There are several studies regarding the relationship between window size and occupant satisfaction. Ne'eman and Hopkinson calculated that in order to obtain a window size that would satisfy at least 85% of the occupants, the window would have to occupy 35% of the wall area [45]. Keighley also found that windows occupying 10% or less of the wall were regarded as extremely unsatisfactory, and the window area should be more than 20% of wall area for minimum standard [46]. Based on these two studies, Farley and Veitch defined the relationship between window size and occupant satisfaction in their paper regarding effect of windows on work and well-being. As described above, the relationship is not directly proportional, but has S-shape curve which can be represented as the figure 23 [47].

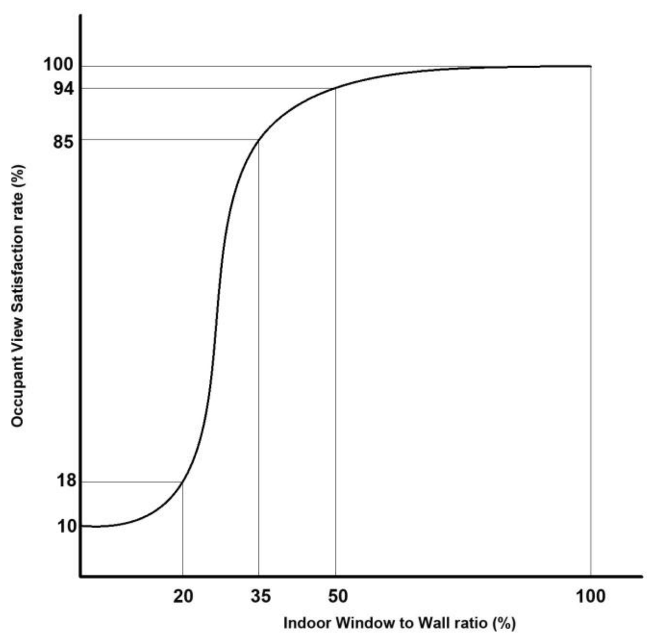


Figure 23. Occupant satisfaction and window to wall ratio

Available Natural Ventilation Hour

Natural ventilation is driven by pressure differences created by temperature differences, wind on building or a combination of these two. The natural ventilation can bring benefit of free cooling as well as occupant well-being such as physical connection to outdoor and healthy indoor air quality. Natural ventilation can also give psychological satisfaction of occupant by self-controllability for their own environment. Natural ventilation, however, can be carefully controlled to prevent excess heating and cooling demand by too hot or too cold outdoor air. Therefore, it is important to check how many hours are available for natural ventilation. The natural ventilation feasible hour can be calculated by comparing the indoor temperature and outdoor dry temperature. When indoor temperature is over cooling set point temperature and outdoor temperature is lower than cooling set point temperature, the hour is counted as natural ventilation feasible hour.

Life Cycle Assessment

Lifecycle assessment (LCA) is a method to quantify the environmental impacts of a product or service, such as greenhouse gas emissions, water pollution, land use, toxins, and more. These impacts can be measured for any or all phases of a product's lifecycle, including manufacturing, distribution, use, and disposal. LCA can be used for many purposes, from helping inform the early stages of the design process to providing detailed data for environmental reporting. The depth and breadth of analysis can vary greatly; take care to match the sophistication of the analysis to its intended purpose [35].

DESIGN PROCESS

Design tools and Energy Modeling tools

A main design tool for this project was Rhino 4.0 with Grasshopper plug-in version 0.8.0066. Although main design was developed by Rhino with Grasshopper, other design tools were also applied for various purposes. Sketch up 8.0 was used for site model and quick concept modeling, and AutoCad 2012 was used to develop detail fabrication. Autodesk Inventor was also used to simulate assembly of all façade components. 3D Studio Max was applied for final rendering. When data need to exchange between design tools, AutoCad Drawing Exchange File (.dxf), or 3D studio (.3ds) were mainly used.

Energy modeling tools were selected based on ability to integrate parametric tools, accessibility (freeware), convenient graphic interface, and appropriateness for early design phase. Even though some tools are not freeware, tools used in this study are available for free student version or free trial version, such as Ecotect, DIVA 2.0. Ecotect 2012 was used for site solar analysis and weather data analysis. DIVA plug-in was used for Radiance/Daysim daylighting analysis on grasshopper interface. For energy demand calculation, normative energy calculator developed by Georgia Tech, EPSCT 1.0 [27], was used. The excel spreadsheet calculator was coupled with grasshopper coding for automatic input data update following by design parameter change. CONTAM 3.1 [33], a multi-zone indoor air quality and ventilation analysis computer program, was applied to calculate annual possible airflow rate through the façade system on the site condition and weather data. For sustainable material study with LCA, existing LCA reports were used to evaluate environmental impact of each material for solid panel selection of façade system. EnergyPlus weather data (.epw) for Inchon was used for all simulation.

Basic Design Approach

Because the work scope of this case study is limited to façade design, the conceptual building geometry was assumed as maximum volume for the site as local building code, and the façade design with parameter sensitivity study for dedicated performance was done with a single story shoe box for convenience in modeling and simulations. The parametric model generated by grasshopper coding can be easily shifted from ground floor to the top floor to simulate each floor performance condition. Major parameters to control in design modeling are window size, ceiling/floor height, lighting shelf, shades, louvers, material properties, and natural ventilation systems.

Grasshopper Coding

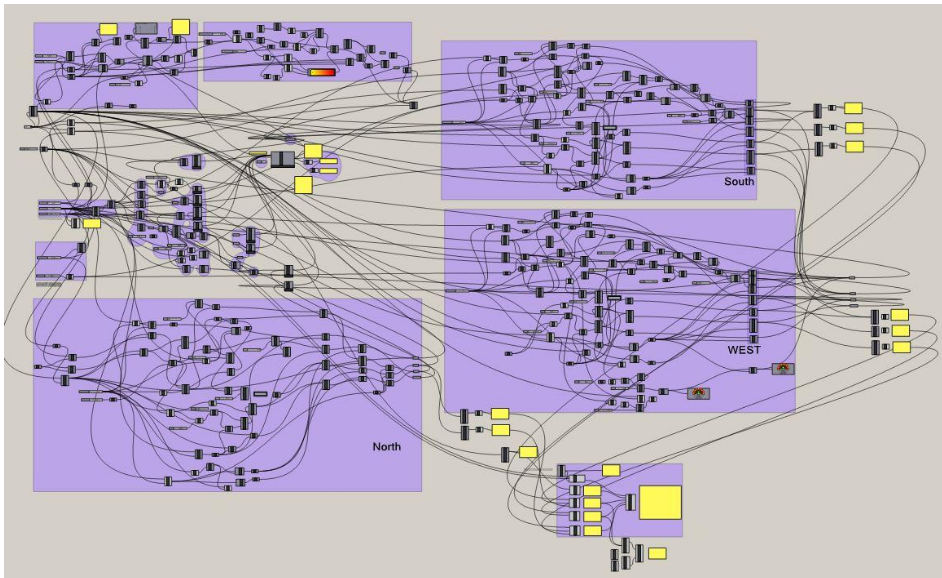


Figure 24. Overall grasshopper code

As introduced previous chapter, grasshopper is based on code scripting using built-in or personalized components written by visual basic script or C+. The components are linked by logics to create a geometry or calculate functions to evaluate the model. The grasshopper coding is simultaneously visualized as 3D objects in Rhino interface.

<u>Basic Geometry</u>

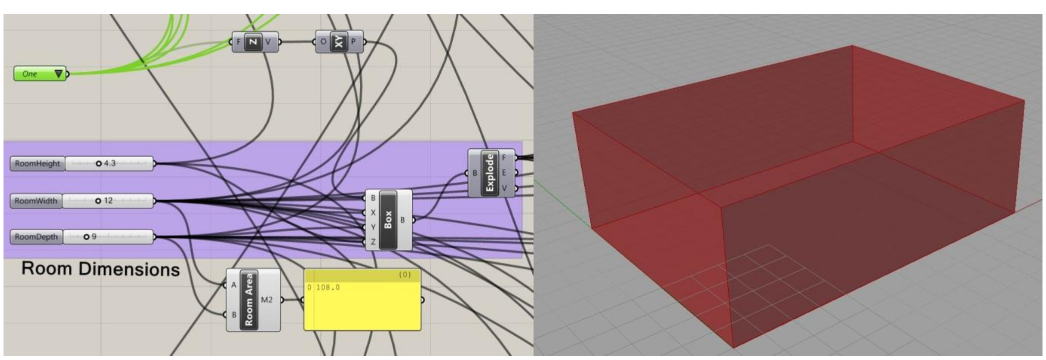


Figure 25. Basic geometry set up: Grasshopper

The model is generated from a simple box to represent the room to analyze the daylighting condition. The room dimensions are controlled by a slide bar which can easily change the dimension parameters. The component shown as ‘one’ indicates the floor level and 3D model is updated for the level as the number is changed.

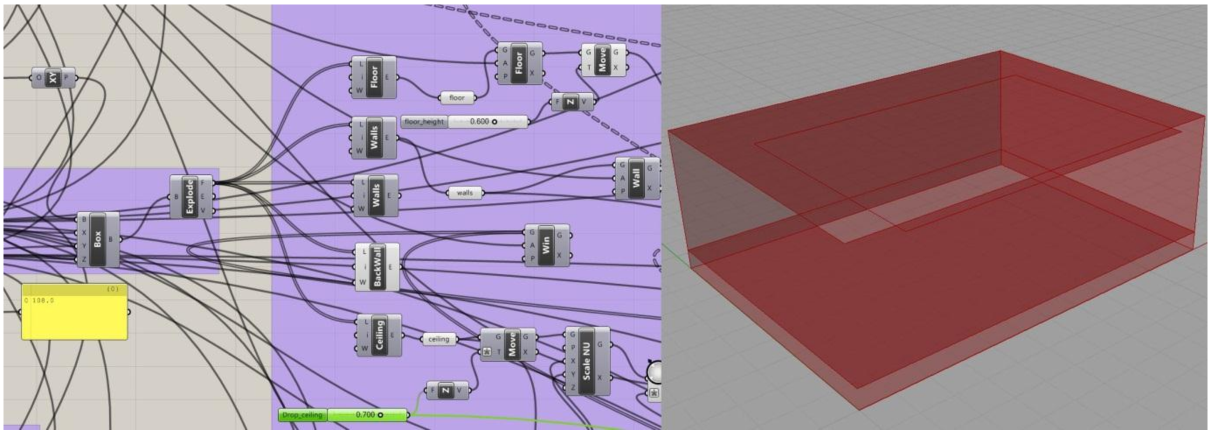


Figure 26. Decompose building components: Grasshopper

The initially defined box is decomposed to each building components as wall, floor, and ceiling for further develop. Floor and ceiling locations are also adjusted for access floor or drop ceiling based on the design.

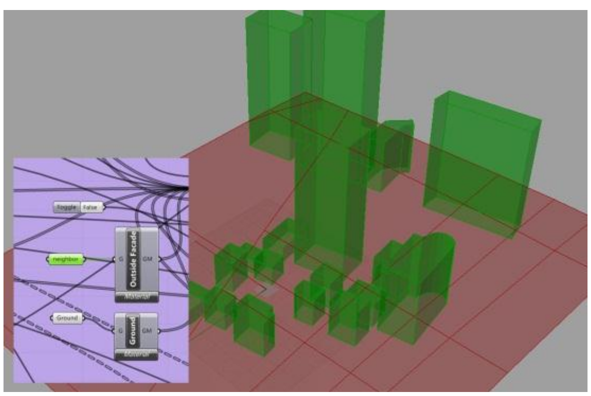


Figure 27. neighbor buildings and ground set up: : Grasshopper

Because neighbor buildings and ground are critical in daylighting simulation, relevant neighbor buildings and ground should be imported into grasshopper from Rhino model. Any objects in Rhino can be easily linked to Grasshopper.

Lighting Analysis Node set up

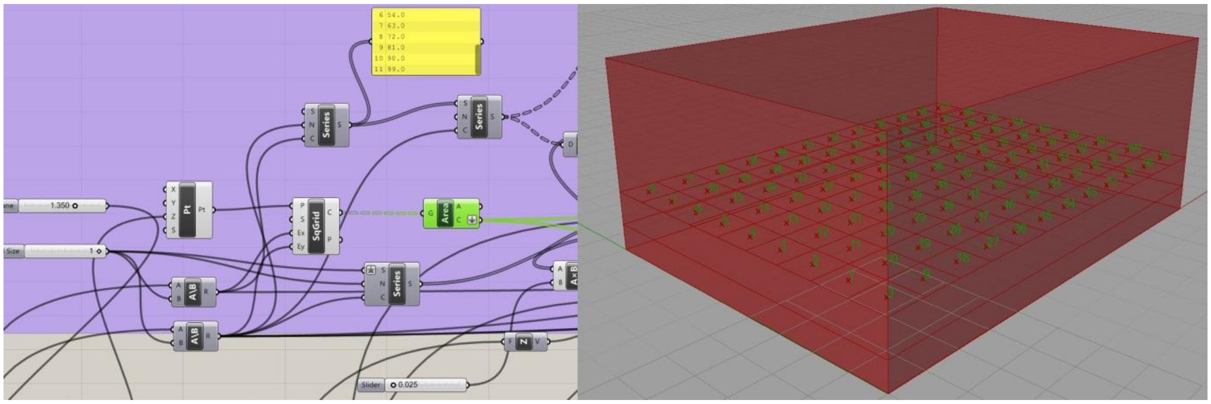


Figure 28. Sensor location set up: Grasshopper

The node points are the location for sensor to measure daylighting level, usually illuminance (lux). The sensors are located on the work plane above 750mm from the floor. The density for node points as well as work plane height are controlled by grasshopper code, and each node point has own ID. By grouping the node data and average value of the group data, lighting condition of the room can be represented as graph or color diagram associated with room geometry.

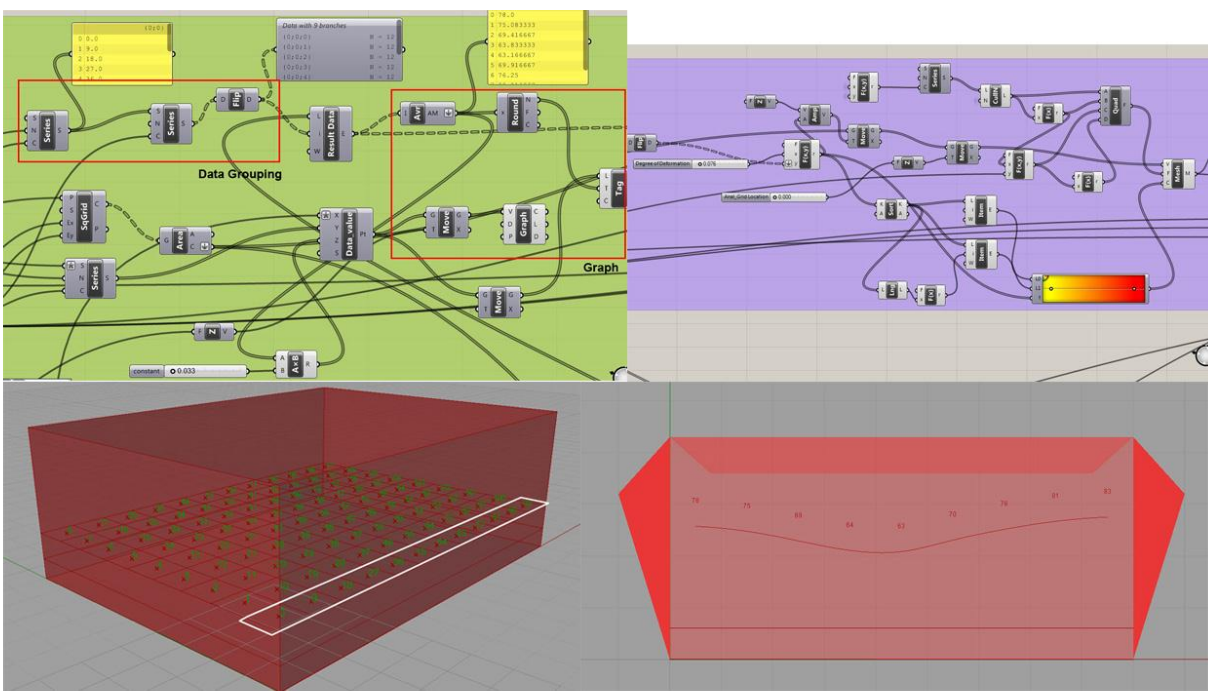


Figure 29. Graph representing simulation result set up: Grasshopper

Façade Modeling

Step 1: Vertical louver and light shelf is added from the original box. Because the geometry of louvers and shades are generated by referencing the original box dimension data, when the box shape is modified, the louvers and shades are automatically updated to match the design logic. Vertical louvers and horizontal shades are also interconnected, and when the depth of shade is changed, the vertical louvers are also extruded based on the depth. The size of window bay is flexibly changed by the shifting the slide bar indicating the number of bay.

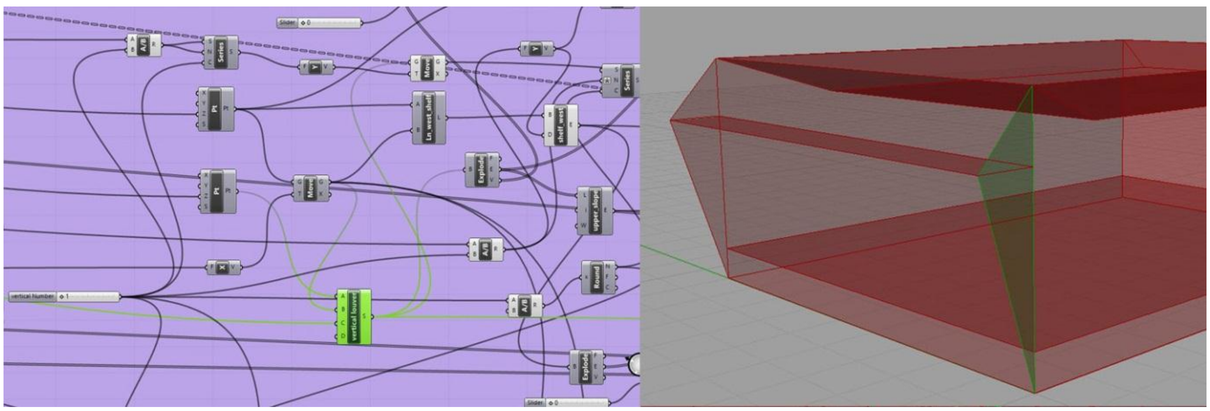


Figure 30. Vertical louver set up: Grasshopper

Step 2: To block heat gain during summer while allowing free solar radiation during heating season with lower solar angle, adjustable louvers are added. The number, depth, and angle are controlled in grasshopper according to the simulation results which can be checked simultaneously with design parameter update.

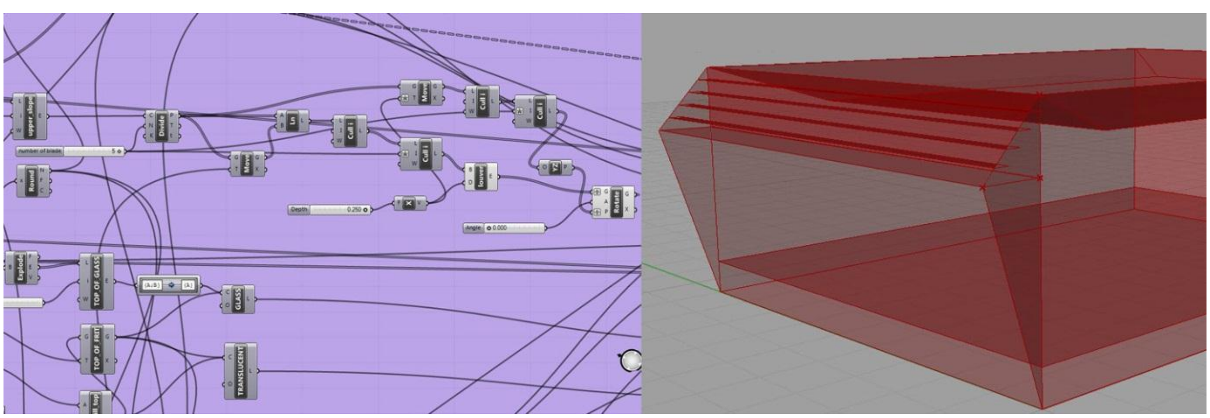


Figure 31. Adjustable louver set up: Grasshopper

Step 3: When the façade has high risk in glare, a lighting diffuser can alleviate the visual discomfort. The parameters for diffuser bars such as position, number, diameters, and materials are also defined with daylighting simulation.

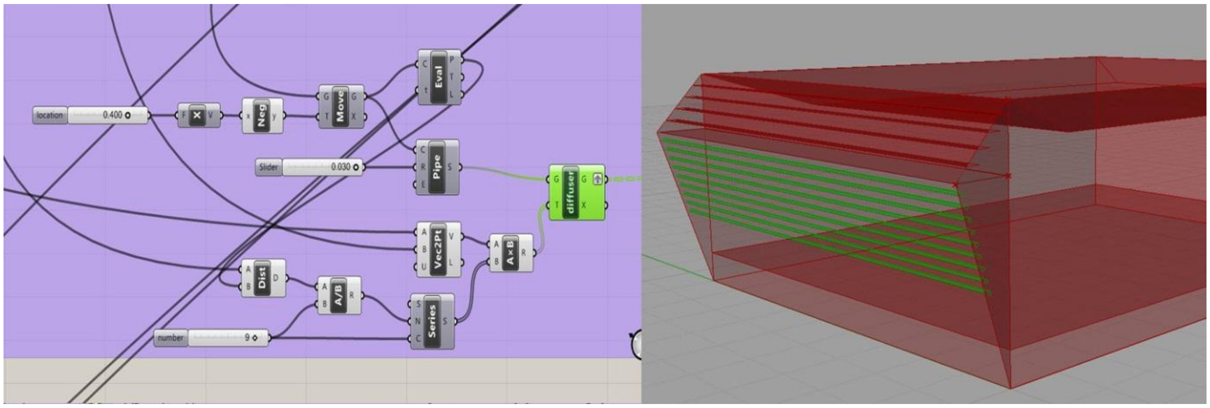


Figure 32. Light diffusing bar set up: Grasshopper

Step 4: The façade is divided several parts to define different type of panel systems. Transparent glass, translucent glass, solid panels, and etc can be integrated on the same façade system, and each position and size should be defined with other panel dimensions.

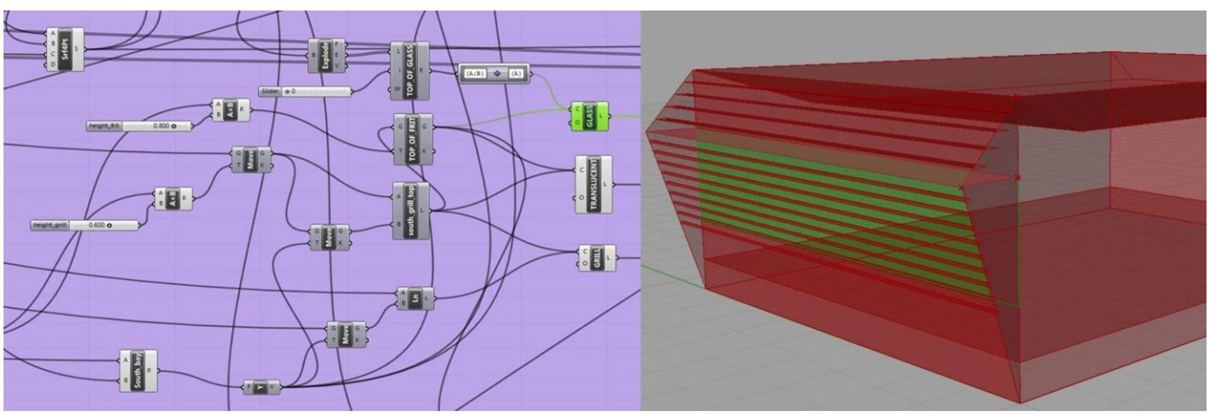


Figure 33. glass panel set up: Grasshopper

Step 5: The façade bay size can be also defined by grasshopper coding. With updating the number of bay, the façade system is automatically updated to devide the elevation with the dedicated size of bay. With little modification of code, different types of bay design can be combined together which can make more various design alternatives in terms of architecture design as well as performance quality.

Each façade has its own script and parameter ranges to define its geometry because each orientation has their own problems in the site context. When the geometries and their parameter ranges are set up, iterative parameter input with matrix should be applied to find out the optimized performance results.

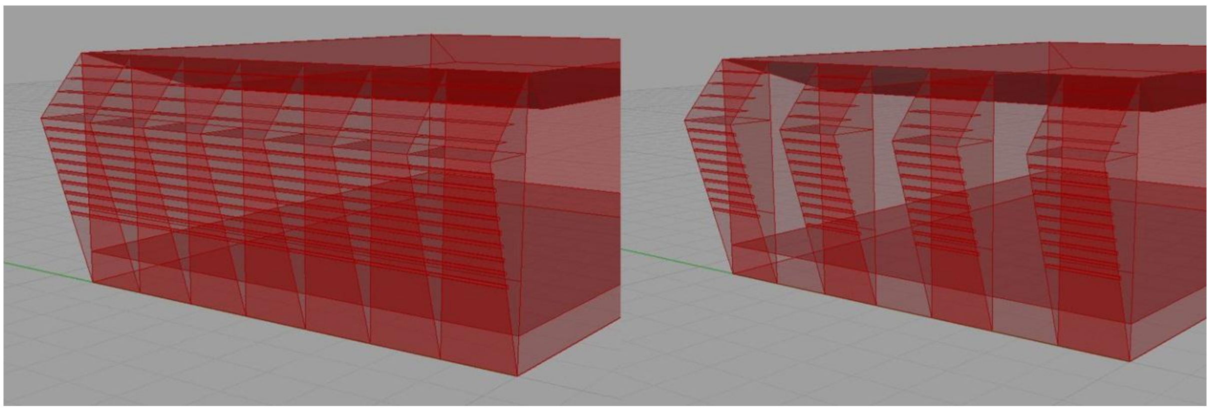


Figure 34. Bay dimension set up: Grasshopper

DIVA set up

When building components are set up, all 3D building objects need to be linked to DIVA components for daylighting analysis. All objects relevant to lighting simulation should be assigned with proper materials first, and linked to the DIVA Daylight component through GM slot. It is very important that neighbor buildings and ground should be included for the lighting simulation. Toggling switch is the activator to run the simulation.

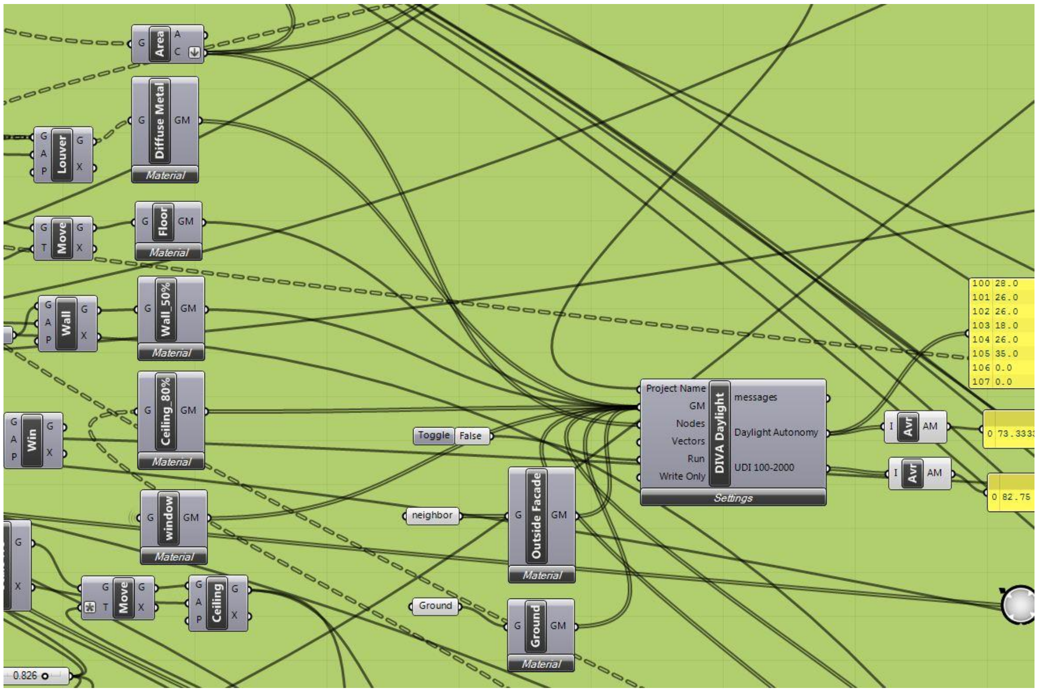


Figure 35. DIVA component set up

The node points for lighting sensors set up before should be linked to DIVA components through 'Nodes' slot.

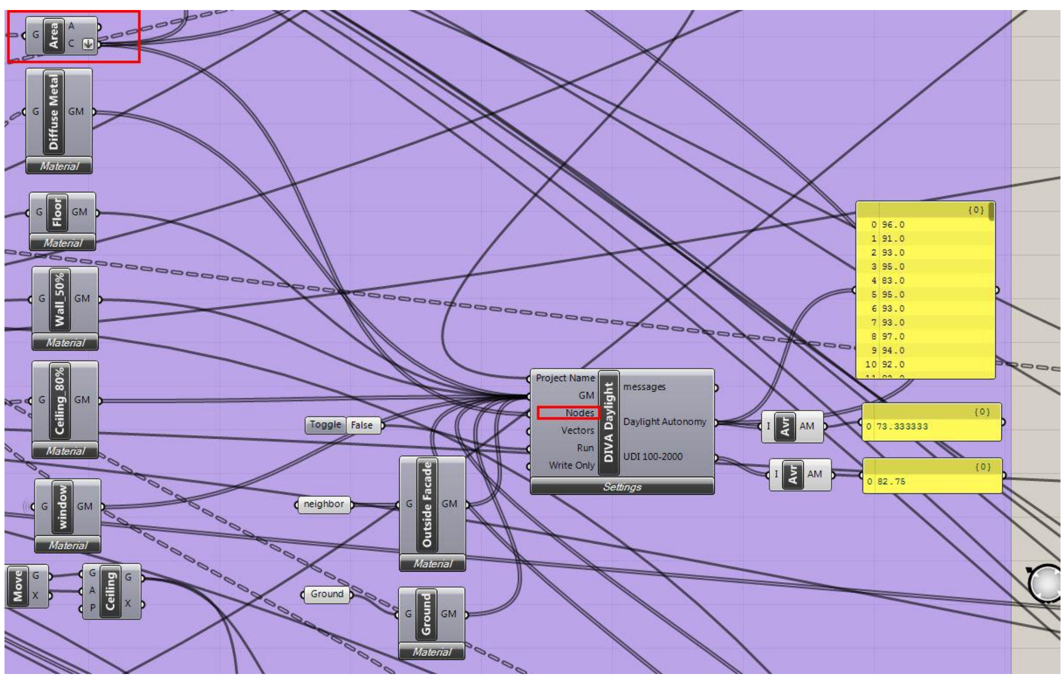


Figure 36. Link nodes to DIVA component

Each material is defined generally from the material library of the simulation engine 'Radiance'. The material components are embedded in the DIVA plug-in, and the customized material can be added with modifying original code of the component. For this lighting simulation, the material application for each building object is shown in Table 2.

Table 2. Material application for building objects in DIVA

Object	Material
Floor	Generic Floor 20% Reflectance
Interior Wall	Generic Interior Wall 50% Reflectance
Louver	Diffuse Metal
Diffuser	Diffuse Metal
Shade	Diffuse Metal
Ceiling	Generic Ceiling 80% Reflectance High Reflectance Ceiling 90% Reflectance
Neighbor Building	Outside Façade 35% Reflectance
Ground	Outside Ground 20% Reflectance
Glass	Double Pane Low e Coating
Translucent Glass	Generic Translucent Glazing 20% Transmittance

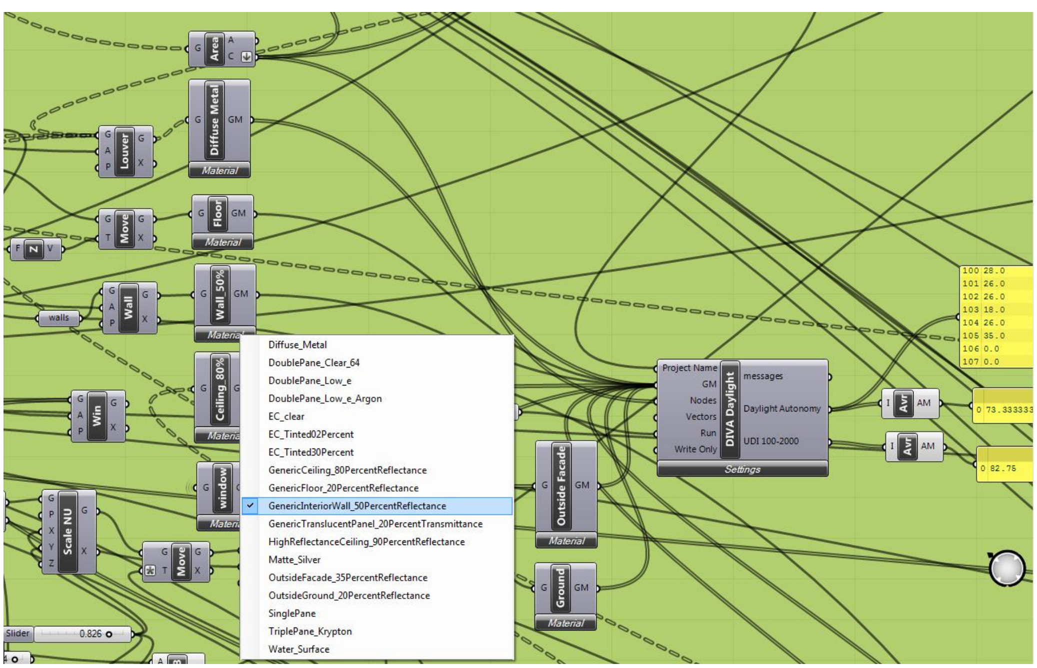


Figure 37. Material set up: DIVA

The DIVA component needs simulation setting with 3 steps. The first step is to import weather data. DIVA mainly uses EnergyPlus weather data (.epw) and the component includes major US cities weather data. The weather data can be added to the component, and the EnergyPlus weather data can be downloaded from the website of US Department of Energy [39].

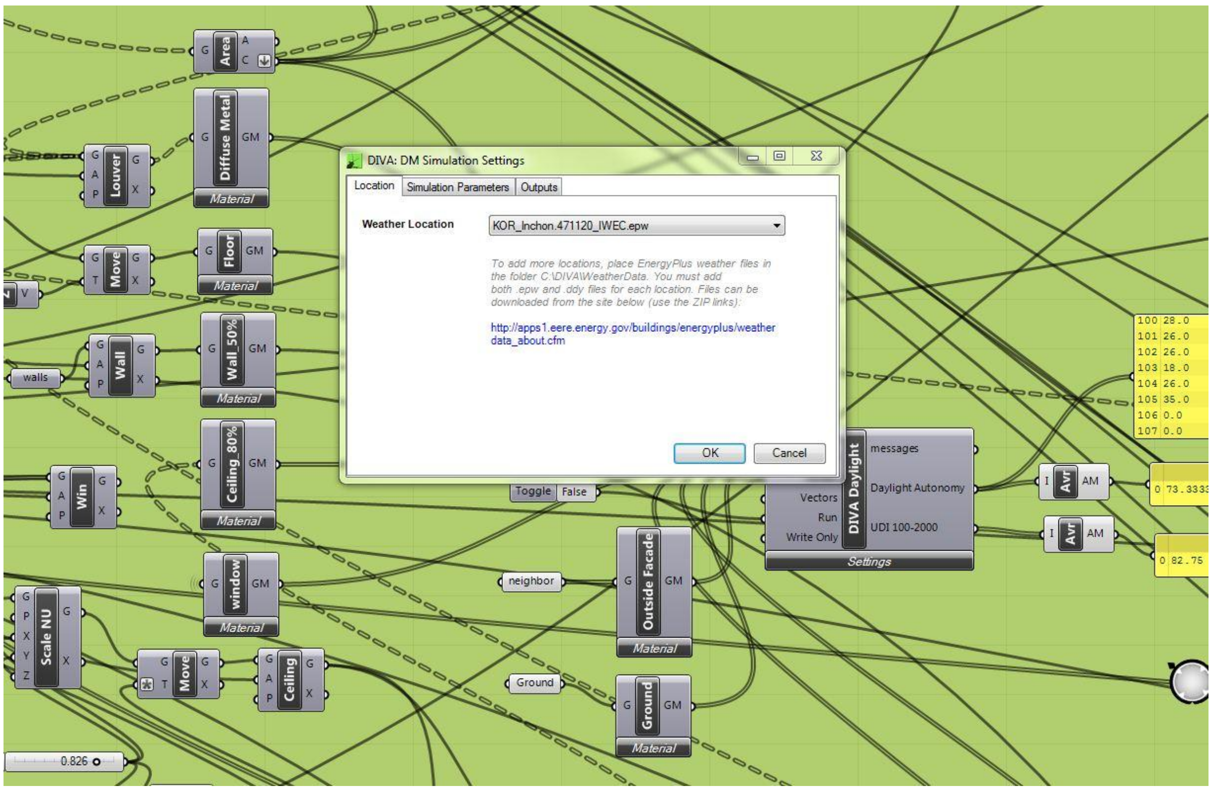


Figure 38. Weather data set up: DIVA

The next step is to define the simulation parameters including metrics and Radiance parameters. DIVA provides simulation to check solar irradiation, daylight factor, illuminance for specific time, climate based metrics, and 3D visualization. Because this simulation needs to check annual daylighting condition considering orientation and actual weather data, climate based metrics is selected. Occupancy schedule was selected as standard office hour 8:00am to 6:00pm, and minimum illuminance level was defined 500lx referred by IESNA Lighting Handbook for office building. The simulation time step was one hour. Non-default Radiance simulation parameters are listed in Table 3.

Table 3. Radiation simulation parameter

Ambient Bounces	Ambient Division	Ambient Sampling	Ambient Accuracy	Ambient Resolution	Direct Threshold	Direct Sampling
4	1000	20	0.1	300	0	0

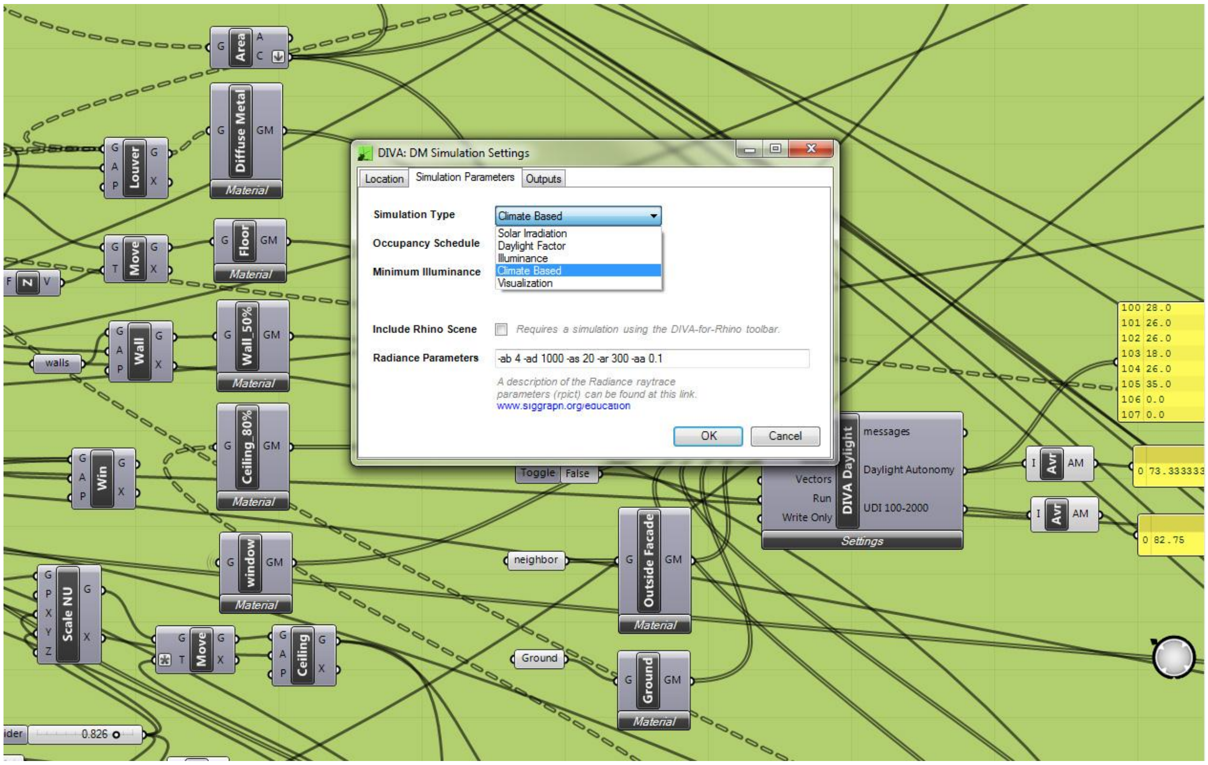


Figure 39. Simulation type set up: DIVA

Last step is to select the output data. Even though there are 6 different format in climate based simulation, it can be distinguished into two main criteria for our use; Daylight Autonomy and Useful Daylight Illuminance. Continuous Daylight Autonomy is recently proposed by Rogers, is another set of metrics that resulted from research on classrooms [34]. In contrast to earlier definitions of daylight autonomy, partial credit is attributed to time steps when the daylight illuminance lies below the minimum illuminance level. For example, in the case where 500lx are provided by daylight at a given time step, a partial credit of 400lx/500lx = 0.8 is given for that time step. The result is that instead of a hard threshold the transition between compliance and non compliance becomes softened. In this case study Daylight Autonomy and Useful Daylight Illuminance 100-2000 are selected. Both of metrics are represented as percentage (%). When the output data format is selected, the format is indicated on the component. After the simulation, the result can be seen on the outlet. The result is connected to the data sorting/grouping component and represented as 2D graph or 3D color diagram.

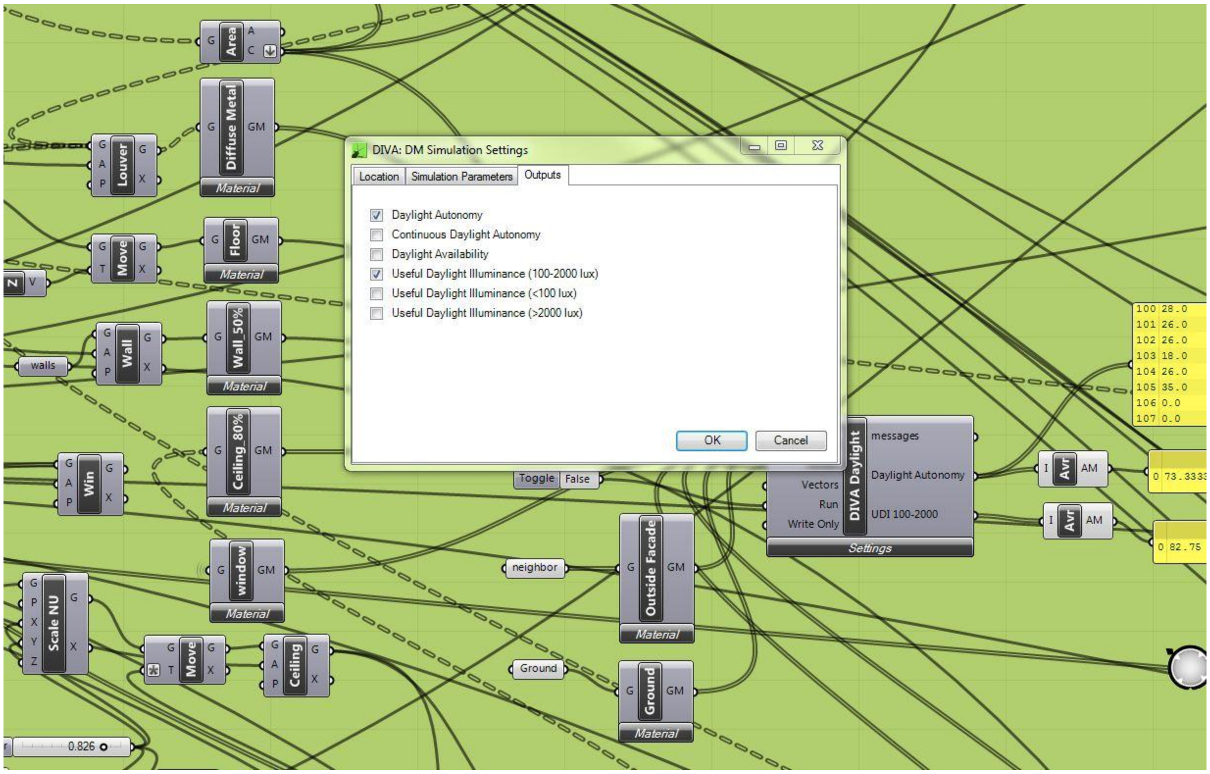


Figure 40. Simulation Output set up: DIVA

<u>Design Information Link set up</u>

DIVA provides energy simulation using EnergyPlus engine, but it is very limited in control and still unstable in information exchange. This case study uses EPSCT, a normative energy calculator, to compare energy demand for design alternatives, and required input data such as window area, wall area, room volumes, are easily prepared

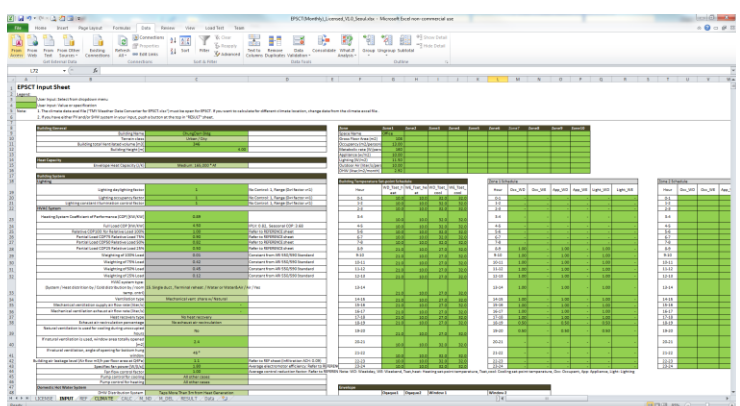


Figure 41. EPSCT energy calculator

by grasshopper scripting, which can save tremendous time to prepare energy calculation. The data can be directly linked to EPSCT, and the input data is automatically updated and by design parameter change. When the data is updated, the EPSCT data is also automatically updated without time consuming iterative works. This set-up makes convenient and fast to compare several design alternative performances.

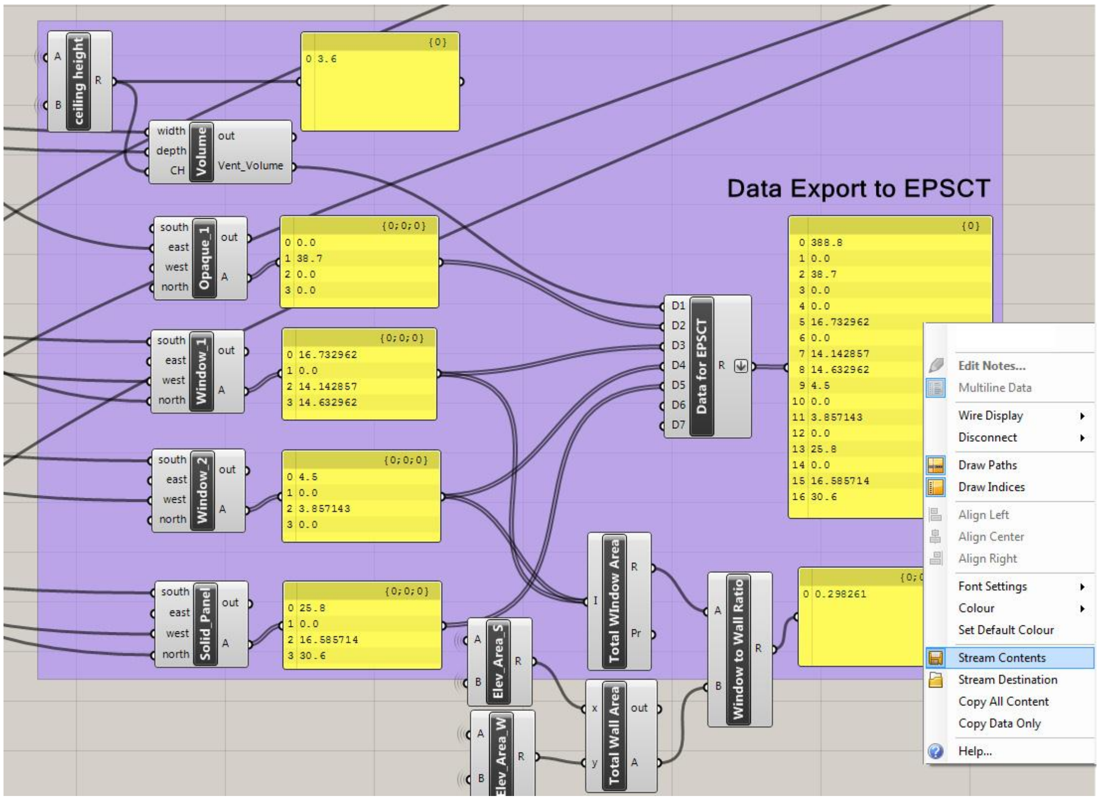


Figure 42. Data export set up

Sensitivity Study

In the daylighting simulation, each key player building component for daylighting performance has different sensitivity in the relationship between its parameter change and the total lighting condition, and the relationships can be defined as normative function for heuristic methodology for daylighting design in the early design stage. The grasshopper coding can allow quick design parameter sensitivity study for the primitive assumption and control for daylighting performance with building components, which can save time and labor in expensive daylighting simulation.

Daylight Autonomy / UDI by Window to Wall Ratio (WWR)

Because the building design has openings for south, north, and west façade, the sensitivity study for window to wall ratio regarding daylight autonomy and UDI (100 to 2000lx) used grasshopper model with half size in room depth (4.5m). As seen on the table 4 and figure 43, daylight autonomy is not so much affected by window to wall ratio because the room depth is relatively small. Even with 25% opening area over 80% of the year can satisfy the minimum illuminance level, 500lx.UDI, however, shows big difference according to the value of WWR. It shows that this building may have problem in visual comfort by glare rather than bringing more light inside.

Table 4. DA/UDI by window to wall ratio

WWR	25	30	35	40	45	50	55	60	65	70
DA	80.3	85.4	87.7	89.7	91.8	93.1	93.7	94	94.3	94.4
UDI	71.5	62.8	57.2	50.4	41.9	32	28.4	26.1	24.2	23.4

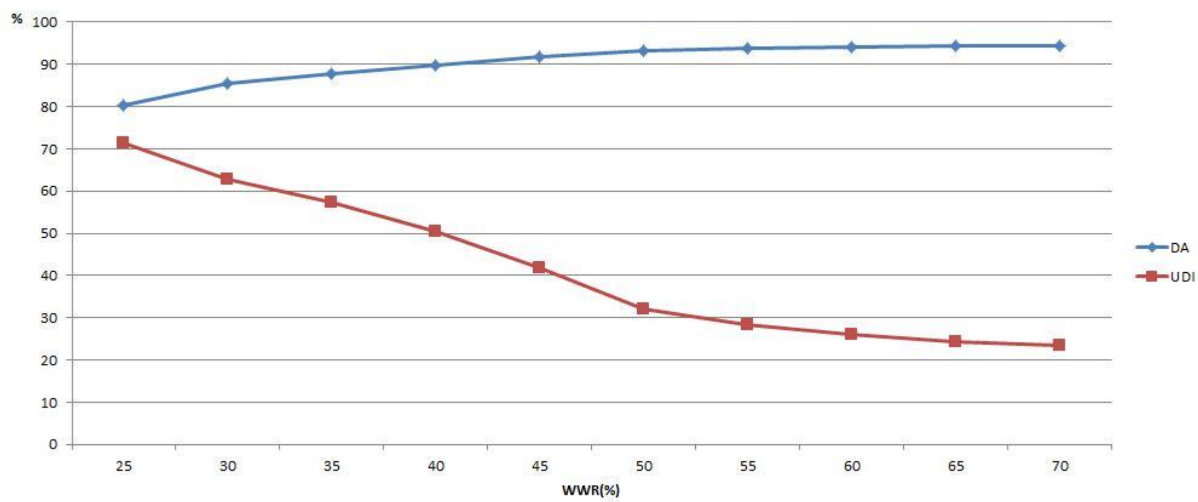


Figure 43. DA/UDI by window to wall ratio

Energy Demand (kWh/m^2.yr) to Wall Ratio (WWR)

The functional relationship between energy demand and window to wall ratio is very proportional. Obviously window to wall ratio is very sensitive in energy demand, and the window thermal property is another critical parameter for the building energy performance. Two type of glass with different thermal value, one is typical 24mm double glazing (U=2.5) and the other is typical triple glazing (U=1.4), were applied. As the U-value increase, the rate to increase energy demand by window to wall ratio also becomes larger. Considering daylight condition for the building, this project may be more practical to have relatively low WWR in case the opening area can satisfy the indoor daylight level target.

Table 5. U-value and window to wall ratio

WWR	25	30	35	40	45	50	55	60	65	70
U=1.4	64	66	68	70	72	75	77	79	81	83
U=2.5	70	74	77	80	83	87	90	94	97	100

U (Window U-Value) = W/m^2K

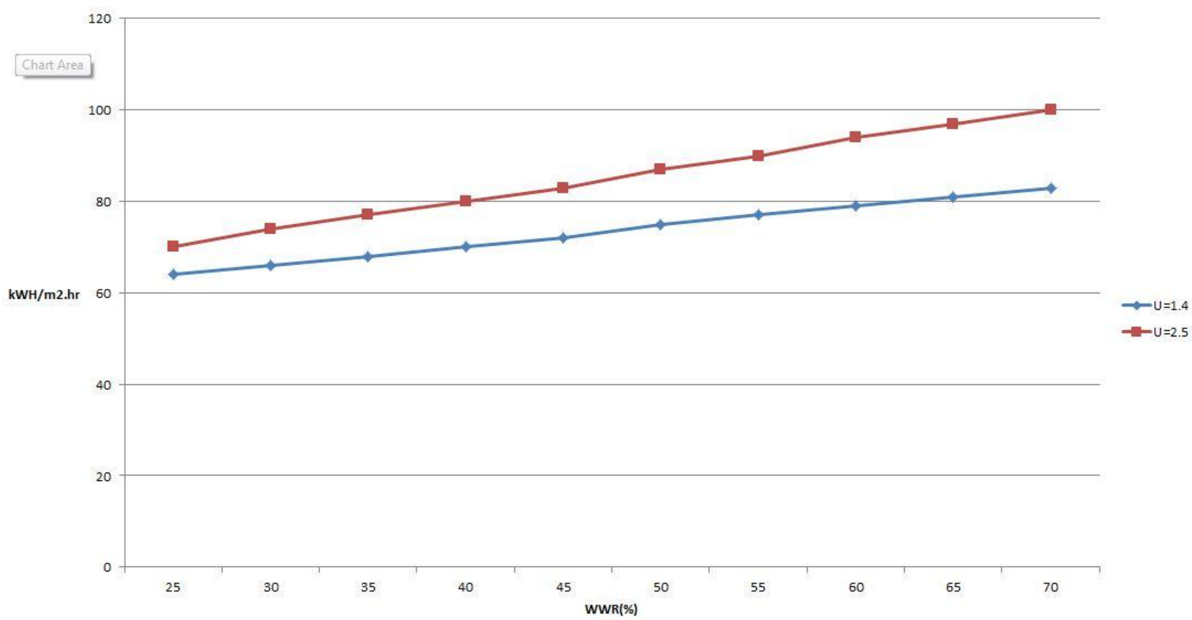


Figure 44. U-value and Window to wall ratio

<u>Horizontal Solar Louver: Louver Depth/WWR/Daylight Factor</u>

Table 6. Horizontal louver depth/WWR/DF

	0	1/8d	1/4d	3/8d	1/2d	5/8d	3/4d	7/8d	d
25%	1.87	1.74	1.64	1.53	1.45	1.36	1.24	1.17	1.09
30%	2.3	2.1	2	1.9	1.8	1.7	1.6	1.5	1.43
35%	2.85	2.6	2.4	2.27	2.1	2	1.9	1.8	1.73
40%	3.51	3	2.73	2.58	2.4	2.3	2.2	2.1	2.01
45%	4.21	3.6	3.16	2.9	2.74	2.6	2.5	2.4	2.32
50%	4.45	4.2	3.9	3.5	3.1	2.97	2.8	2.7	2.62
55%	5.94	5.3	4.7	4.3	3.9	3.6	3.24	3.1	2.9
60%	6.88	6.2	5.6	5.14	4.7	4.34	4.06	3.86	3.64
65%	7.4	6.7	6.1	5.6	5.1	4.8	4.5	4.2	4
70%	7.7	6.9	6.3	5.8	5.3	5	4.7	4.4	4.2

d=opening height

As seen on the table above, when the solar louver is installed with the depth of window height, the total light intensity can be decreased about 40 to 50% regardless of the window to wall ratio. According to the IESNA (illuminating Engineering Society of North America) lighting handbook, daylighting factor between 2 to 5 is considered good quality of lighting intensity.

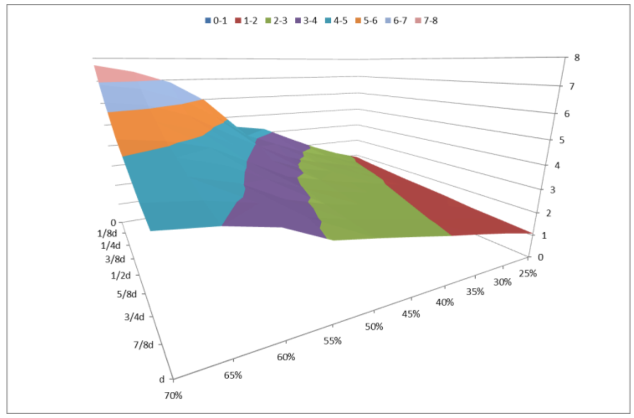


Figure 45. Horizontal Louver/WWR/DF

Vertical Louver Depth/ Number/ Daylight Factor

Table 7.Vertical louver/number/DF

	0	1/4w	1/2w	w	1.5w	Rate
1	6.91	6.3	6.06	6	5.8	0.83
2		6.2	5.87	5.5	5.3	0.76
3		6.2	5.76	5.2	4.96	0.71
4		6.2	5.68	5.2	4.7	0.68
5		6.2	5.66	5	4.5	0.65
6		6.2	5.66	4.9	4.4	0.63

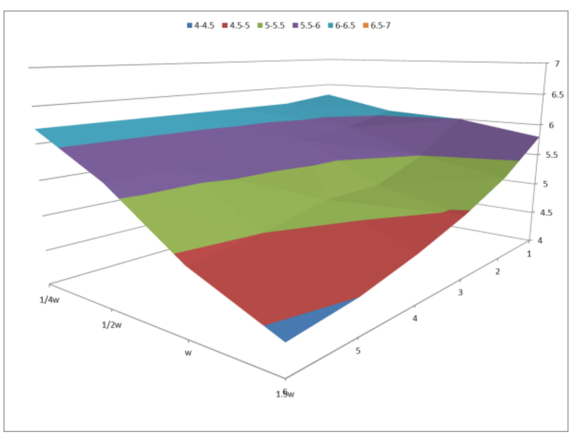


Figure 46. Vertical louver/number/DF

The simulation results show that number of vertical louver is not very sensitive in total lighting performance. Especially after a certain number, the change of lighting intensity is quite negligible. There is more sensitivity in the depth of louver. When the depth of lover change from 0 to 1.5w (w=opening area width next to the louver), the total lighting intensity decrease 10% per 1/4w. The change rate, however, becomes relatively flat after the depth is over 2w.

Light Shelf

In terms of total daylight intensity, the light shelf looks not so sensitive to affect the performance. Although it affect about 70% decrease to the lighting intensity with installation, the parameter change is not very effective in total lighting intensity. The light shelf, instead, results in an evenly distribute the daylighting intensity, which greatly helps to increase the visual comfort with lowering the possibility of discomfort glare.

Table 8. Light shelf height and DF

	800mm	1200mm	1500mm	Rate (to no shelf: DF 7.63)
0.6CH	5.98	5.65	5.37	0.90 (0.7)
0.68CH	6.15	5.86	5.52	0.90 (0.72)
0.77CH	6.25	6.06	5.82	0.93 (0.76)
Rate	0.96	0.93	0.92	

Shelf Height/Depth/Daylight Factor

Table 9. Light shelf angle and DF

	0°	10°	20°	30°	Rate
0.6CH	5.65	6.05	6.26	6.48	0.87
0.68CH	5.86	6.13	6.47	6.56	0.89
0.77CH	6.06	6.3	6.5	6.72	0.9
Rate	0.93	0.96	0.96	0.96	

Shelf Height/ Angle/ Daylight Factor

Design Alternatives

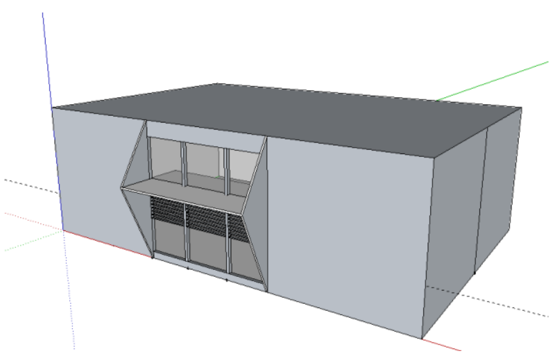


Figure 47. Basic design sketch

The facade geometry is initiated from the basic sketch to define the façade elements to control daylight in the space. This is in contrast with most conventional design processes which complete a design first and review the performance of design with simulation. Our process is set up to compare design alternatives early on and find optimized design parameters through the back and forth workflow with embedded use of simulation. In this case study, 3 design alternatives, generated by grasshopper code variation and design intents, are compared. First alternative is a baseline model, which is typical fully glass covered façade with light shelf maximizing window to wall ratio. The second alternative is to add solar control elements on alt 1, high window to wall ratio scheme, to reduce extra solar gain for saving cooling demand during summer. The façade geometry for alt 2 is also modified to integrate solar control elements with façade design. The third design alternative is to reduce window area to make better in thermal performance of the building. It also tries to reduce the visual discomfort with glare, which may effect on the UDI. All design alternatives are considered to use natural ventilation for free cooling, and the way to ventilate outdoor air will be defined with simulation for airflow.

Table 10. Design alternatives and WWR

Design Options		Alt 1	Alt 2	Alt 3	Remarks
Window to Wall Ratio	Exterior	70%	70%	40%	Exclude east wall
	Interior	90%	90%	50%	

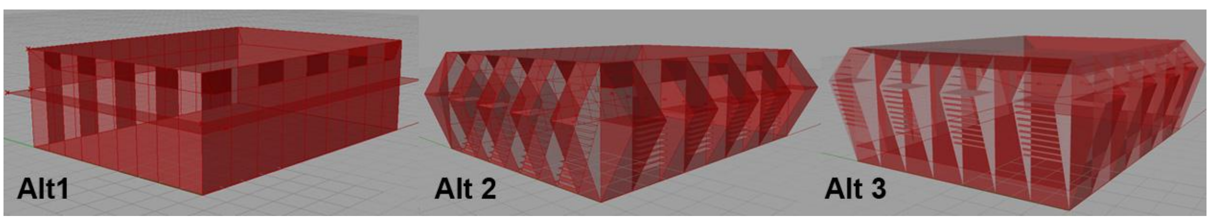


Figure 48. Design alternatives

The occupant view satisfaction is depending on the indoor window portion of the wall as referred in previous chapter and the value can be found with the graph (figure 23). The table 11 shows the occupant view satisfaction for each alternative.

Table 11. Occupant View Satisfaction

Design Options	Alt 1	Alt 2	Alt 3
Occupant View Satisfaction (%)	99	99	94

BUILDING SIMULATION

Daylight Analysis

<u>Alternative 1</u>

Figure 49. Alt-1 Radiance Image

Design alternative-1 can achieve over 500lx in indoor lighting intensity with only daylight for more than 90% of total occupied hour, from 8am to 6pm. Although it has satisfactory daylight autonomy value, this scheme can have some problems in visual comfort because many times the indoor lighting intensity goes beyond 2000lx which can cause glare problem to occupants. Figure 50 regarding UDI shows that more than 50% of total occupied hour have lighting intensity over 2000lx.

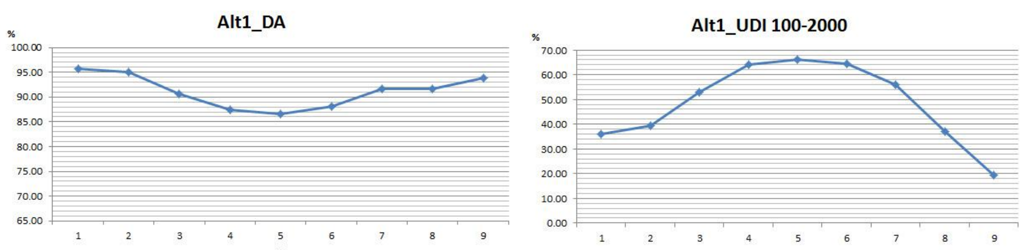


Figure 50. Alt-1 DA and UDI value

Figure 49 shows the daylight analysis image by Radiance based on the illuminance simulation on June 21st at noon. Sky condition is clear day without direct sun on facade. As seen in figure 51, most of the floor daylight level is over 2000lx on the simulation time.

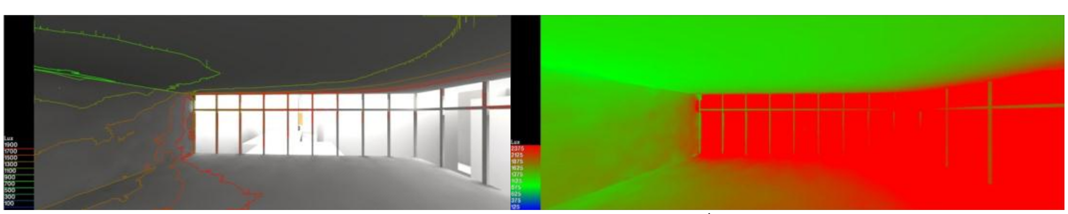


Figure 51. Alt-1 Radiance illuminance simulation for June 21st 1200pm

Alternative 2

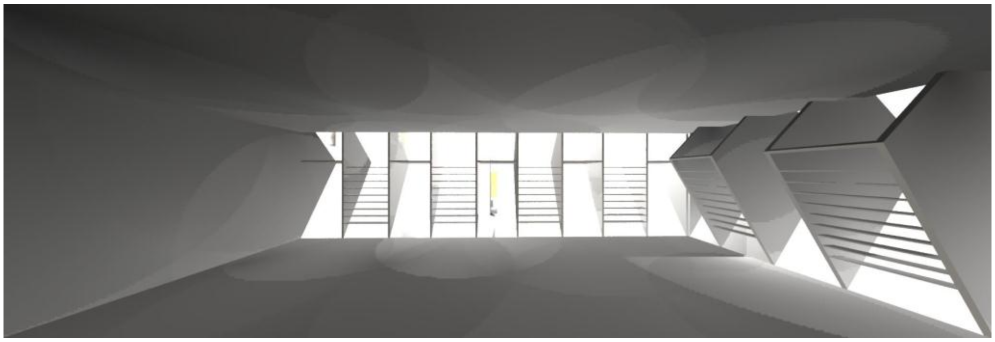


Figure 52. Alt-2 Radiance Image

Design alternative-2 also can achieve over 500lx in indoor lighting intensity with only daylight for more than 90% of total occupied hour, from 8am to 6pm. With keeping daylight autonomy value over 90%, the play of lighting control façade elements, light shelf, shades and louvers, alleviate the extreme lighting condition. UDI 100-2000 graph shows that over 60% of occupied time is within the daylight level of 100 and 2000lx at most of area except near window perimeter.

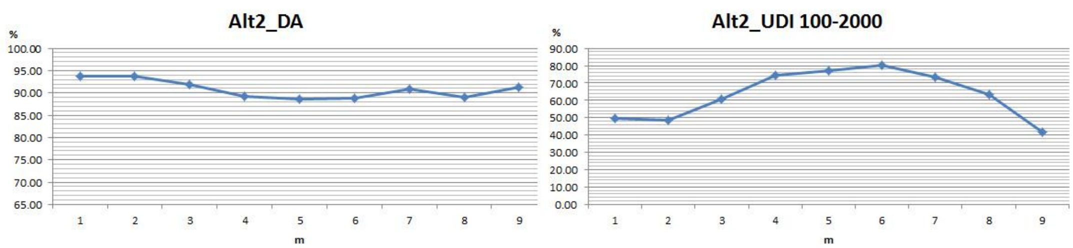


Figure 53. Alt-2 DA and UDI value

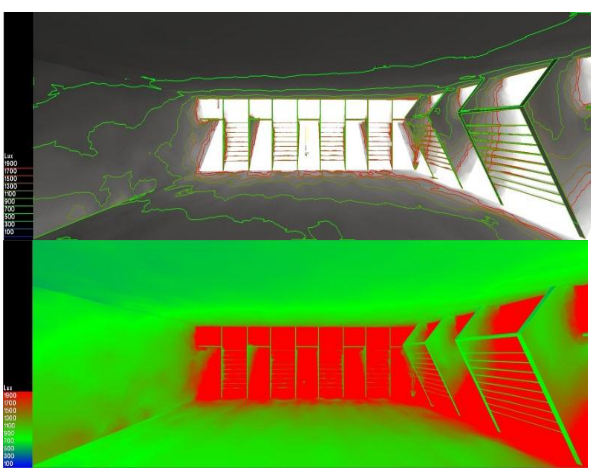


Figure 54. Alt-2 Radiance illuminance simulation

Figure 52 shows the daylight analysis image by Radiance based on the illuminance simulation on June 21st at noon. Sky condition is clear day without direct sun on the facade. As seen in figure 54, indoor daylight level is much lower than alt-1. The lighting level is mostly between 1000 and 2000lx.

Alternative 3

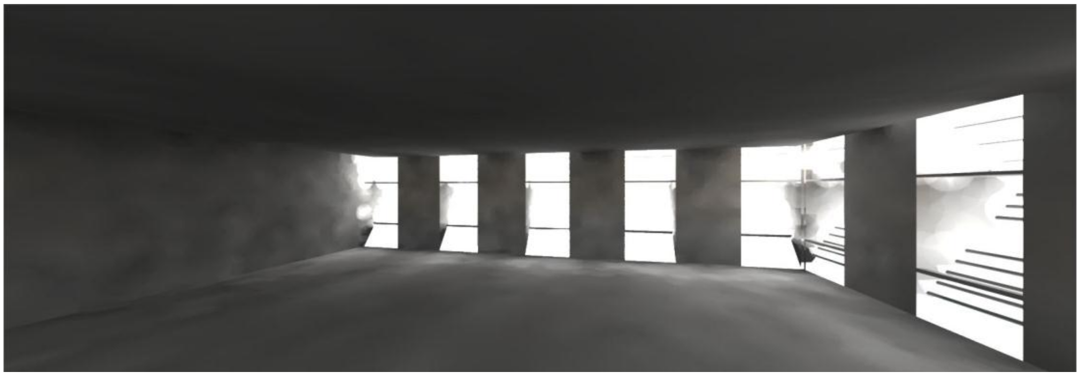
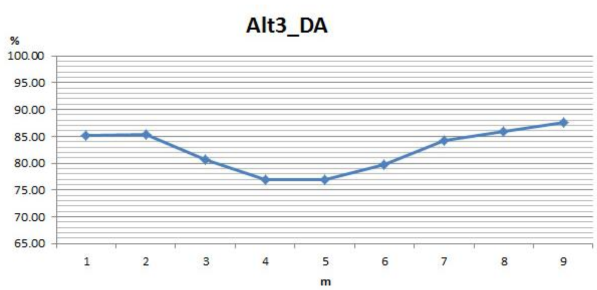


Figure 55. Alt-3 Radiance image

According to the previous sensitivity study, daylight autonomy in this building is not affected by window to wall ratio because of the relatively shallow depth of room. The window to wall ratio is more directly related to annual energy demand and visual comfort issue. Therefore, this alternative tries to reduce window to wall ratio to almost half of other schemes, 40%, which shows relatively high daylight autonomy and high UDI 100-2000 value in the sensitivity study. As shown in the graph below, the reduced window to wall ratio doesn't much sacrifice the indoor daylight level. Its average daylight autonomy is 82.5% which is about 90% of other alternatives. However, the average UDI 100-2000 value is changed to about 86% which is 40% higher than alt 2 and even almost 100% higher than alt 1.



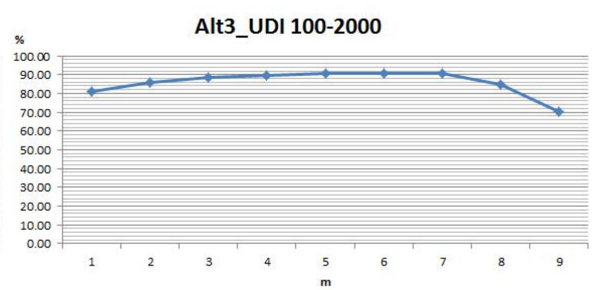


Figure 56. Alt-2 DA and UDI value

Figure 55 shows the daylight analysis image by Radiance based on the illuminance simulation on June 21st at noon. Sky condition is clear day without direct sun on the facade. As seen in figure 57, indoor daylight level is very well distributed. The lighting level is mostly between 400 and 1000lx.

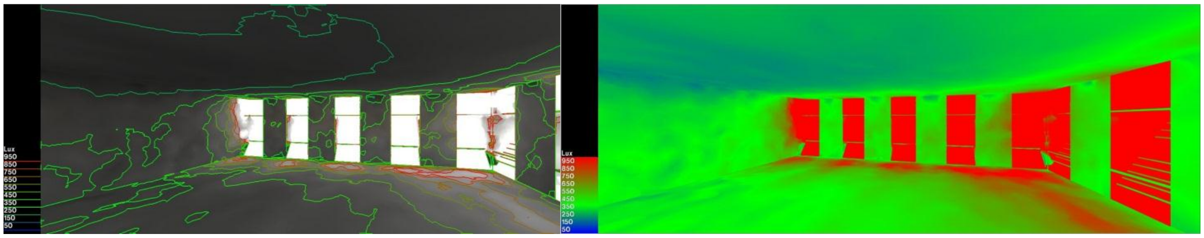


Figure 57. Alt-3 Radiance illuminance simulation

Result Summary

The graph below shows how each design alternative has different light conditions.

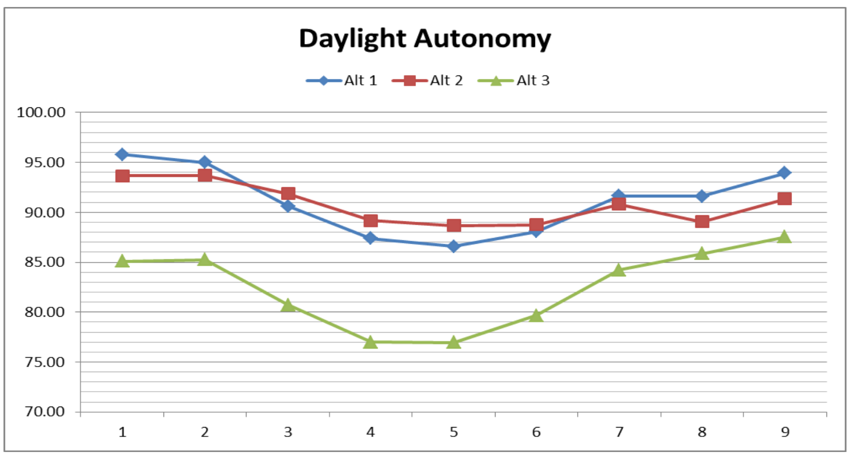


Figure 58. DA values of Design Alternatives

Alt 1 and alt 2 shows very similar value in daylight autonomy. Even though in the average value for alt 1 has slightly higher than alt 2, on the relatively deeper area alt 2 shows better performance because the light shelf and blinds distribute daylight better than alt 1. Alt 3 shows the lowest value in daylight autonomy, but its average is over 80% which doesn't seriously hurt the indoor lighting quality.

In terms of visual comfort, alt 3 shows outstanding value compared to other alternatives as shown on the UDI graph. Alt 3 UDI value is relatively flat on the room location, and it indicate that the alt 3 has not only moderate lighting value but also less contrast in indoor lighting level which can minimize the glare problems.

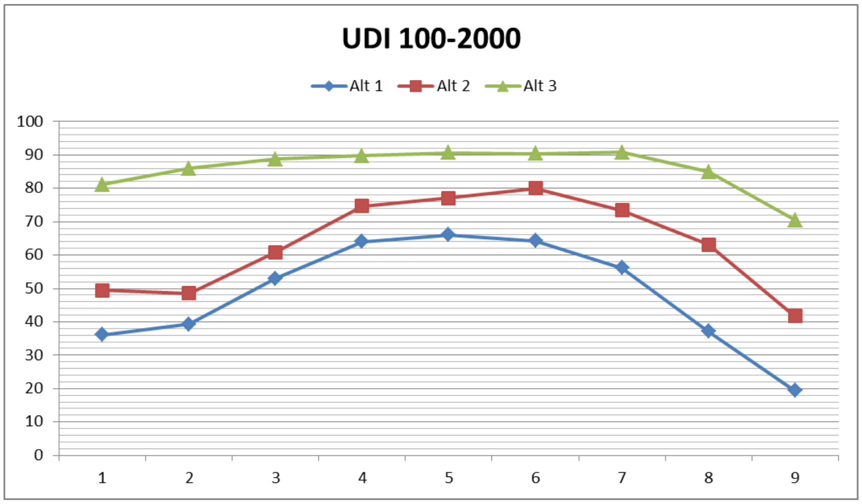


Figure 59. UDI 100-2000 values of Design Alternatives

Energy Demand Analysis

<u>Input Data Set Up</u>

Because the purpose of the energy demand analysis is not to predict exact actual energy consumption during operation but to compare multiple design alternatives, the input data is mostly regarding building geometry and major material properties. The calculation is also done for the single floor office zone, not for whole building, because the target of this experiment is to compare the energy efficiency of different façade system and the metric is energy demand per square meter during a year. The major concern is energy demand side, so the energy delivery value is not critical in this stage because mechanical system is not defined yet. Most of input data is regarding building geometry, material properties, operation schedule with temperature set point, and internal load data. Internal load data used reference information from ASHRAE such as ASHRAE 90.1, and ASHRAE handbook of fundamentals. Operation schedule and temperature set point is followed by the energy guideline for office building issued by Korea Energy Management Corporation in 2009, 26℃ for cooling and 20℃ for heating during occupied hour; 8am to 6pm weekday. The input data for internal load is as Table 12.

Table 12. Input data for internal load

Internal Load	Units	Value	Remarks
Occupancy	m^2/person	20	
Metabolic Rate	W/person	88	ASHRAE Handbook of Fundamentals. Chap 9,Table 4
Appliance	W/m^2	10	
Lighting	W/m^2	10	
Outdoor Air	liter/s/person	9.73	
DHW	Liter/m^2/month	5.7	ASHRAE 90.1 Chap 49, Table 6

Major materials for façade system are transparent glass, translucent panel, high pressure laminated panel system and green roof. Detail information and material properties are in Table 13.

Table 13. Material properties for building enclosure

Material	Composition	Properties	Remarks
Glass	Low-e double glazing 12mm argon + 6mm clear glass	Visual Transmittance: 70% Emissivity : 0.14 Solar Transmittance: 31.1% Solar emissivity: 0.29 U factor: 1.25 W/m^2K SHGC: 0.39 Shading Coefficient: 0.45	
Translucent Panel	75mm thick panel with aerogel infill	Light Transmittance: 20% U factor: 0.30 W/m^2K	
Solid Panel	8mm HPL panel + rigid insulation + 200mm CMU block + batt insulation + gyp board	U value: 0.28W/m^2K Emissivity: 0.58	
Solid Wall	300mm HW concrete + batt insulation + gyp board	U value: 0.266 W/m^2K Emissivity: 0.920 Heat Capacity: 631.6 kJ/m^2K	
Roof	Green roof	U value: 0.24	

Alternative 1 Energy Demand

Month	Heating Need [kWh/m2]	Cooling Need [kWh/m2]
Jan	13.62	1.00
Feb	9.88	1.46
Mar	4.97	2.80
Apr	1.06	5.22
May	0.10	8.26
Jun	-	12.26
Jul	-	14.32
Aug	-	16.05
Sep	-	10.98
Oct	0.27	5.67
Nov	3.76	2.06
Dec	10.32	0.94
Total [kWh/m2/yr]	43.96	81.02

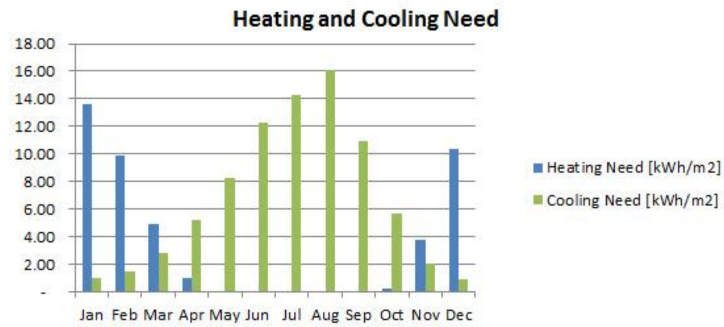


Figure 60. Alt-1 monthly energy demand

Alternative 2 Energy Demand

Month	Heating Need [kWh/m2]	Cooling Need [kWh/m2]
Jan	16.19	0.45
Feb	12.34	0.65
Mar	6.78	1.33
Apr	1.64	2.77
May	0.16	5.08
Jun	-	8.57
Jul	-	10.80
Aug	-	12.28
Sep	-	7.34
Oct	0.45	3.10
Nov	5.07	1.02
Dec	12.27	0.47
Total [kWh/m2/yr]	54.91	53.86

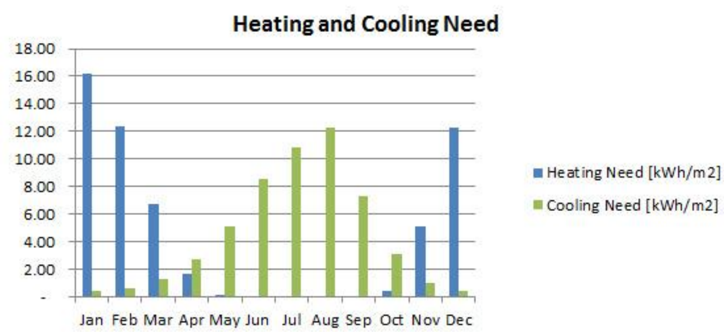


Figure 61. Alt-2 monthly energy demand

Alternative 3 Energy Demand

Month	Heating Need [kWh/m2]	Cooling Need [kWh/m2]
Jan	12.41	0.27
Feb	9.66	0.37
Mar	5.07	0.84
Apr	1.16	1.88
May	0.08	3.87
Jun	-	6.87
Jul	-	8.94
Aug	-	10.04
Sep	-	6.07
Oct	0.25	2.39
Nov	3.73	0.69
Dec	9.12	0.30
Total [kWh/m2/yr]	41.48	42.53

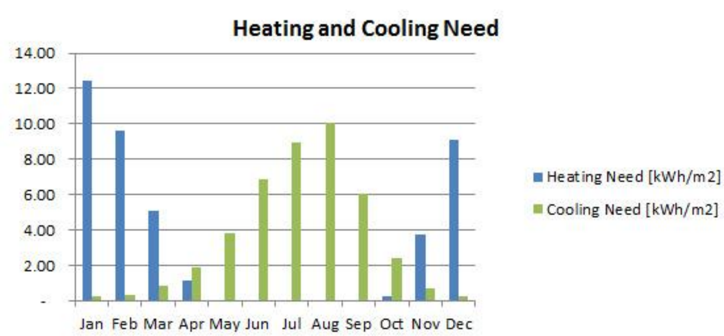


Figure 62. Alt-3 monthly energy demand

Result Summary

Table 14. Energy demand for design alternatives

Alt	Energy	Demand [kWh/m^2/yr]	Total [kWh/m^2/yr]
Alt 1	Heating Need	44	**125**
	Cooling Need	81	
Alt 2	Heating Need	55	**109**
	Cooling Need	54	
Alt 3	Heating Need	41.5	**84**
	Cooling Need	42.5	

Due to blocking solar radiation with solar control devices on façade, alt 2 reduced cooling need in comparing to alt 1. Alt 2, however, couldn't get the free heating benefit during winter season, which increases the heating need. Alt 3, reducing glazing area and applying various solar control elements on façade system, reduced building energy demand in both heating and cooling. The energy demand of alt 3 is about 67% of alt 1 and about 77% of alt 2. It is important to notice that the EUI data is exclusively for comparing design alternatives. It is based on a set of normative usage scenarios that can differ from the real use of the building.

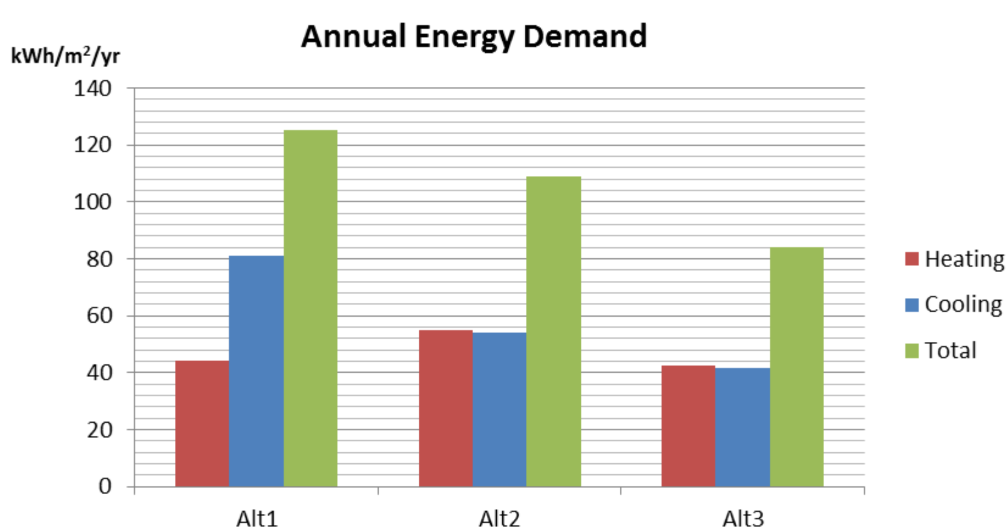


Figure 63. Annual energy demand of design alternatives

Natural Ventilation

Natural Ventilation Feasibility for free cooling

Natural ventilation is always very attractive energy saving method in sustainable design, but it's not easy to achieve valid performance without considering all design factors and the effect of local site & climate conditions. The valid hours for natural ventilation can be calculated by the estimated thermal load and outdoor temperature. The figure 64 shows the relationship between indoor temperature and outdoor temperature. When the indoor temperature exceeds the cooling set point temperature and outdoor temperature is below the cooling set point temperature, direct ventilation cooling can usefully offset internal heat gains to maintain thermal comfort. EPSCT energy calculator was used to estimate the valid hours for free cooling with natural ventilation.

The outside temperature is not enough to evaluate the feasibility of natural ventilation because the building design and urban wind condition should allow enough mass flow for air exchange between outdoor air and indoor air. To evaluate the airflow capability of building, CONTAM was used to calculate air change rate per hour (ACH). The ACH is calculated as annually, and it can be used to estimate how much the building can be cooled down by natural ventilation and offset the cooling load.

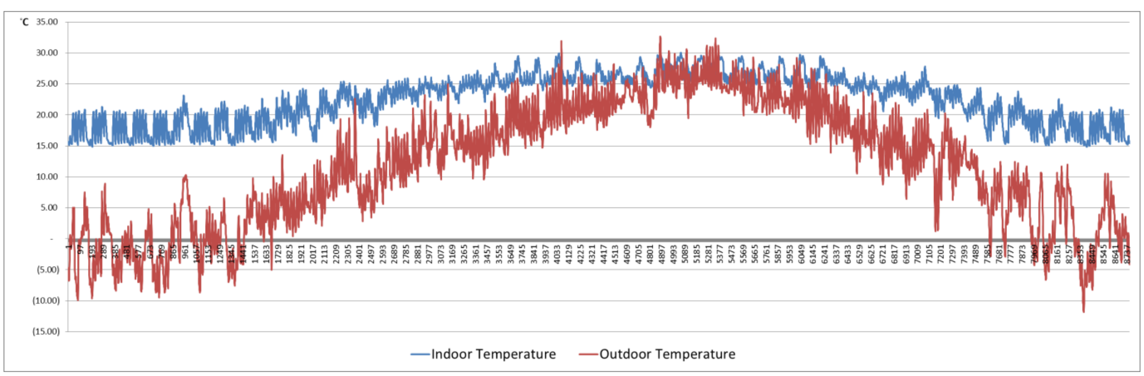


Figure 64. Hourly Outdoor/Indoor temperature variation

Design Concept

Considering the outside noise and controllability, natural ventilation is considered with air inlet located in low part (under floor) of south and west façade system. The air induced through the inlet comes up through the floor diffuser, and exhaust through ceiling plenum to air outlet on north façade. The inlet and outlet are better to be controlled automatically by temperature sensors, but it can be also operable by occupants for their personal comforts. The natural ventilation system can be coupled with fan coil units installed under the access floor to offset the heating and cooling load near window area.

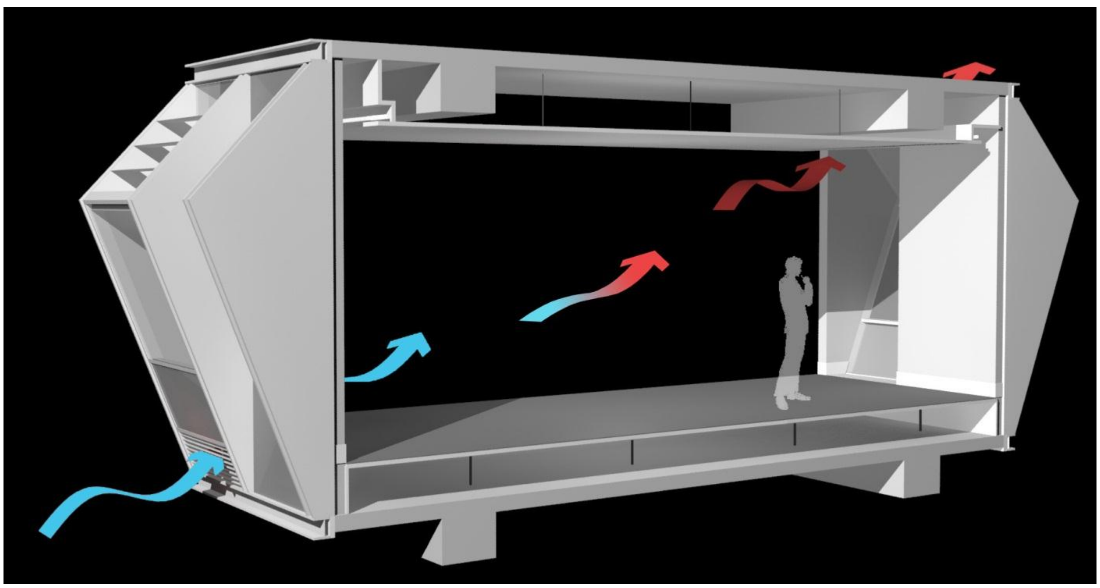


Figure 65. Natural ventilation airflow concept

Cp Calculation

C_p is the wind pressure coefficient. The wind pressure coefficient defines what portion of the wind kinetic energy is transformed to pressure energy on the vertical surface. Air flow is usually induced by pressure difference, so CONTAM needs C_p values for each facade to calculate building surface pressure. The static air pressure (p_w) on building surface [Pa] is defined by the following formula;

$p_w = C_p \cdot (\rho_a \cdot v^2 /2)$ ρ_a: ambient air density (kg/m^3), v: wind velocity [28]

C_p can be roughly calculated by web based calculator [40] using weather data and some data input regarding building geometry and urban context. The geometry data is used as simplified form, and the site representation on the C_p calculator is as figure 66.

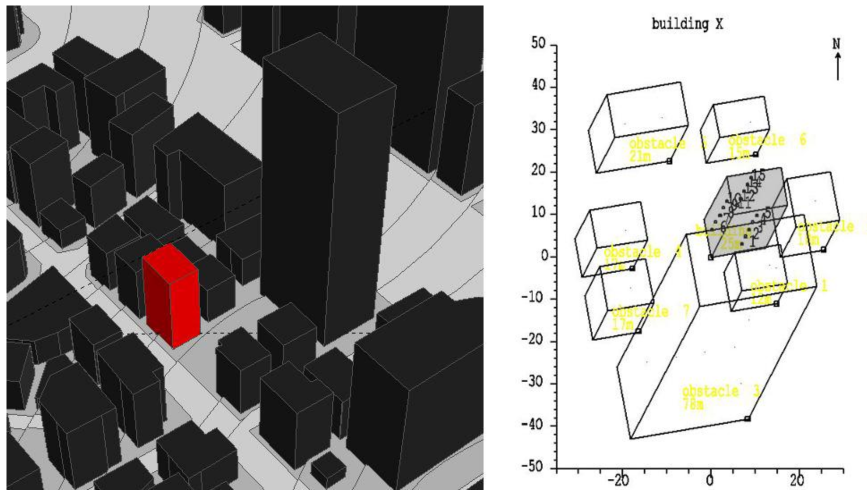


Figure 66. Site representation on Cp calculator

The node point is defined by each floor height on south, west and north wall. Because a neighbor building is located very close to east side of the building and there is no opening on east facade, the C_p on east wall didn't calculated. The node location and one of the original results is shown on the figure 67.

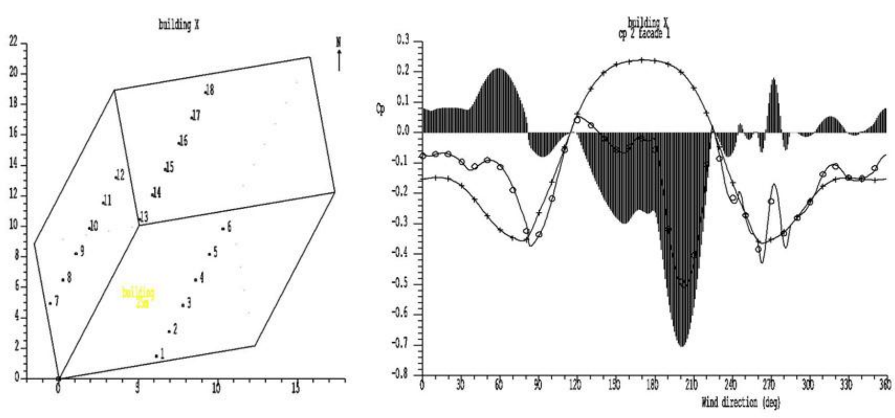


Figure 67. Node location and Cp value for a node

The total C_p data used for CONTAM simulation over each of 3 facades is shown on the graph below with wind angle from 0 to 360.

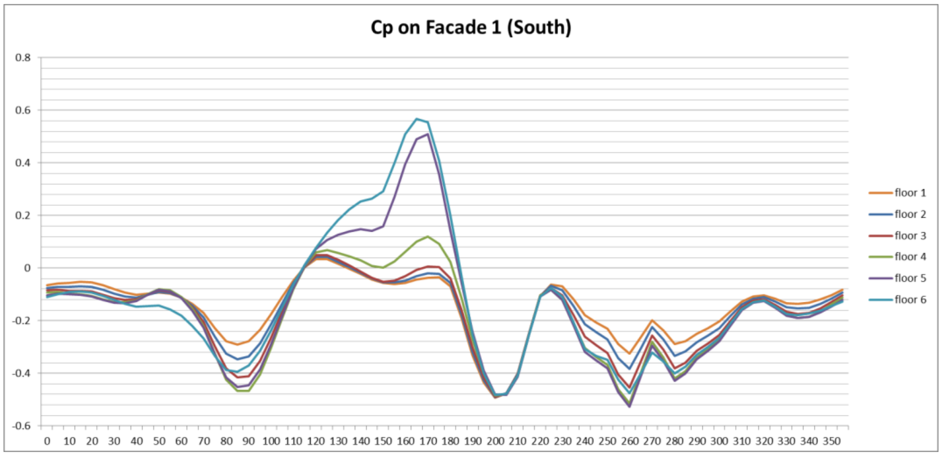


Figure 68. Cp values on south facade

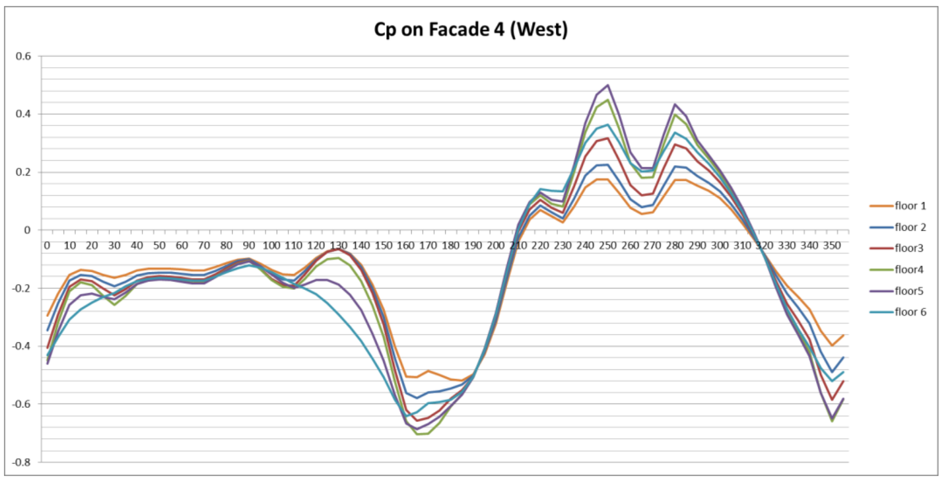


Figure 69. Cp values on west facade

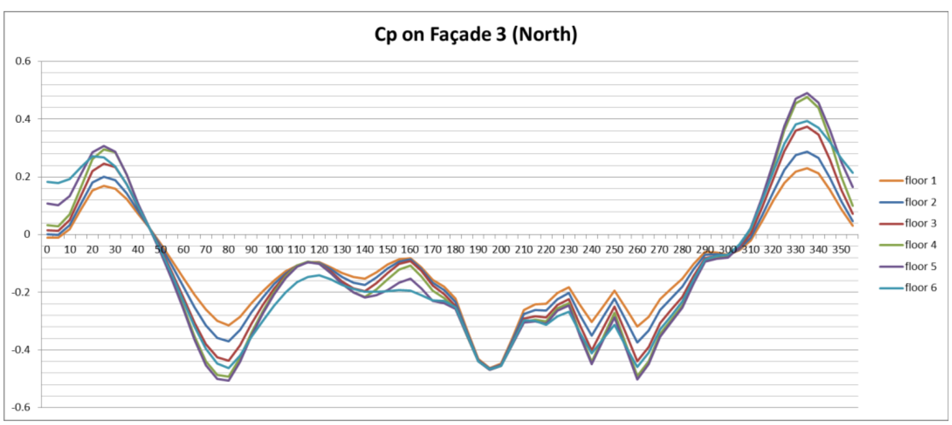


Figure 70 Cp values on north facade

Air Change Rate Calculation by CONTAM

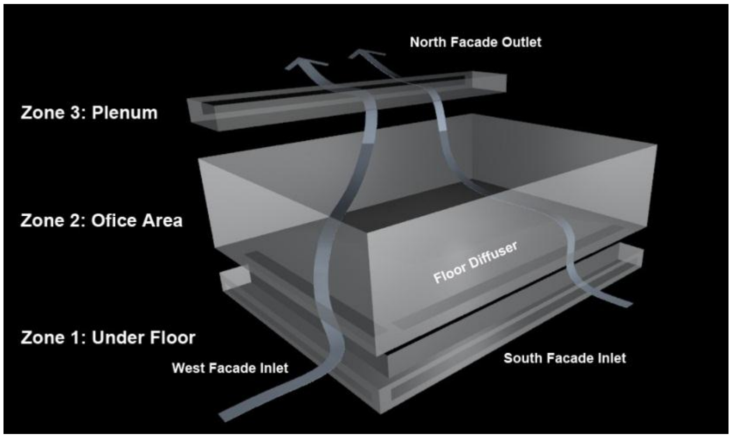


Figure 71. 3D representation of CONTAM airflow model

Air change rate for each floor is calculated by CONTAM. The simulation model is composed of 3 zones where ventilation air travels through; under floor air inlet, office zone, and ceiling plenum air outlet as figure 71. Airflow path model type is 'One-way flow using power law', and formula is applied as 'Leakage area data'. Each zone properties are as following Table 15.

Table 15. Input data for CONTAM simulation

	Zone 1 (Under Floor)			Zone 2 (Office)			Zone 3 (Plenum)		
Volume (m3)	6.15			324			4.2		
Floor Area (m2)	10.25			108			6		
Pressure (Pa)	Various			Various			Various		
Temperature (℃)	Constant (20)			Constant (20)			Constant (20)		
Flow Element	South Inlet	Area (m2)	2.8	South floor Diffuser	Area (m2)	1.0	Ceiling Plenum	Area (m2)	1.0
		Discharge coefficient	1		Discharge coefficient	1		Discharge coefficient	1
		Flow exponent	0.6		Flow exponent	0.65		Flow exponent	0.65
		Pressure difference [Pa]	4		Pressure difference [Pa]	4		Pressure difference [Pa]	4
		Wind speed modifier	0.25						
	West Inlet	Area (m2)	2.0	West floor Diffuser	Area (m2)	2.8	North Outlet	Area (m2)	2.4
		Discharge coefficient	1		Discharge coefficient	1		Discharge coefficient	1
		Flow exponent	0.6		Flow exponent	0.65		Flow exponent	0.6
		Pressure difference [Pa]	4		Pressure difference [Pa]	4		Pressure difference [Pa]	4
		Wind speed modifier	0.25					Wind speed modifier	0.25

The estimation results of hourly air change rate floor by floor by CONTAM are shown in following graphs.

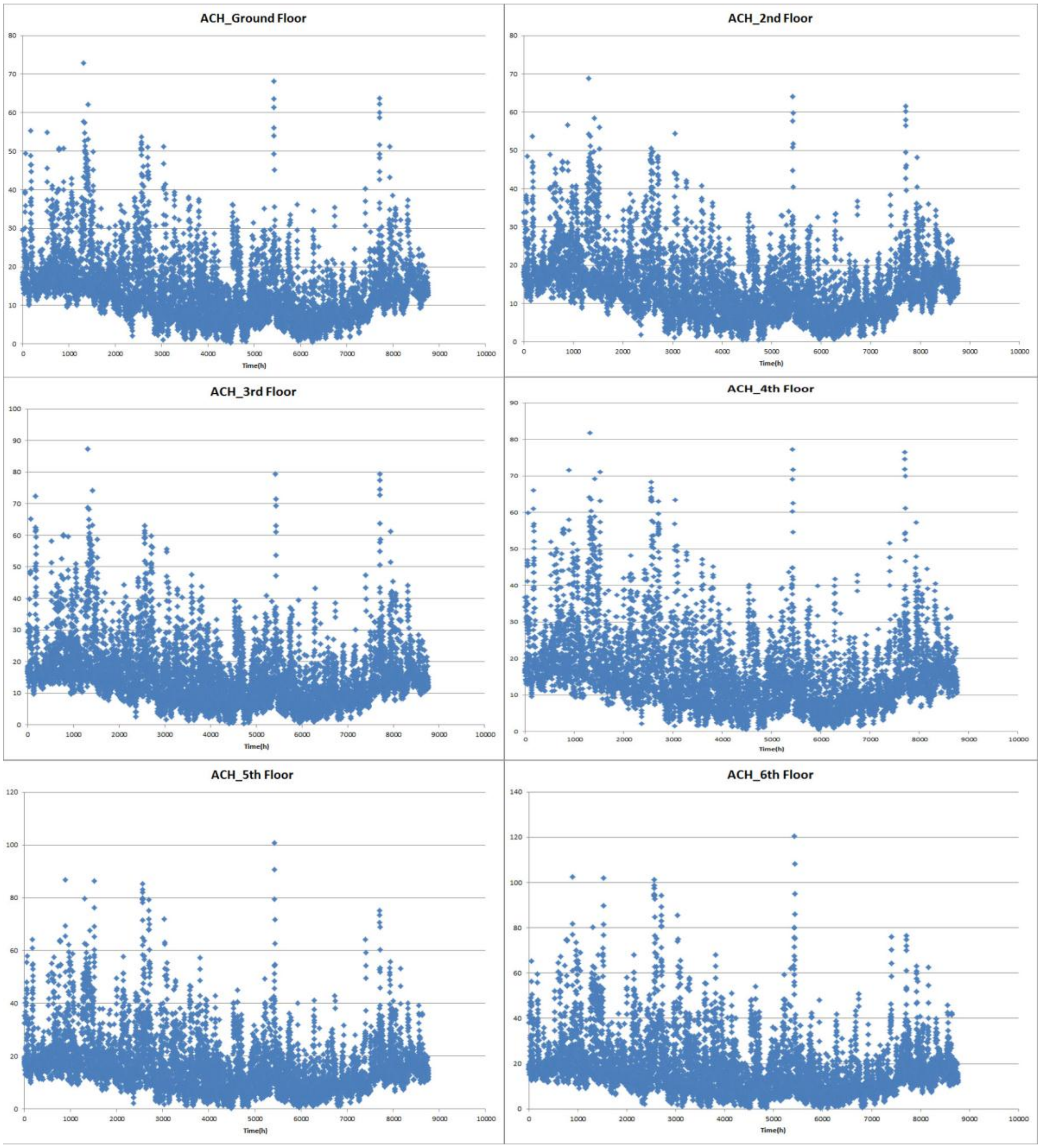


Figure 72. Hourly air change rate for each floor

The average value of air change rate in each floor is on Table 16. The value is in the case when the inlet and outlet is fully open.

Table 16. Average air change rate in each floor

Floor	AVG. ACH
Ground	13.51
2nd	14.11
3rd	15.08
4th	15.63
5th	15.96
6th	17.26

Potential Cooling Energy Saving Calculation

EPSCT tool was used to check available hours for free cooling by natural ventilation. It calculates the hours by counting the hour when indoor temperature exceeds cooling set point temperature ($T_{c.set}$) while outdoor temperature is lower than $T_{c.set}$ [28]. When the available cooling hour is defined, the calculated hourly air change rate value is applied to estimate how much cooling load is offset with free cooling.

- **Alt 1**

Total available cooling hour for alt 1 is 754 hours which is about 30% of total operation hours. As swing seasons June and September have longest hours for natural ventilation benefit, and even July and August also have decent number. Because this calculation didn't consider humidity and thermal comfort, it may not be able to consider this number with high reliability, but it can be good clue to compare design alternatives for natural ventilation feasibility.

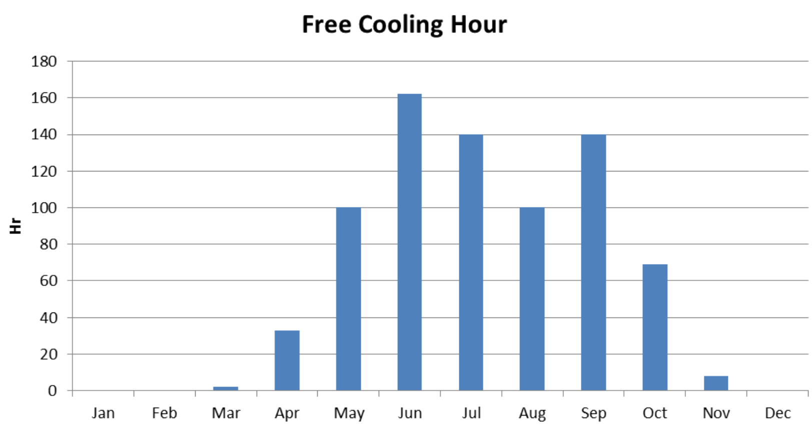


Figure 73. Monthly free cooling hour in Alt-1

The total saving in cooling load by natural ventilation is 27kWh/m^2/yr and it is about 33% of calculated cooling load without considering natural ventilation benefit. With the free cooling benefit, total energy demand for alt 1 is reduced from 25kWh/m^2/yr to 98kWh/m^2/yr. The figure 74 shows the monthly cooling load differences with natural ventilation.

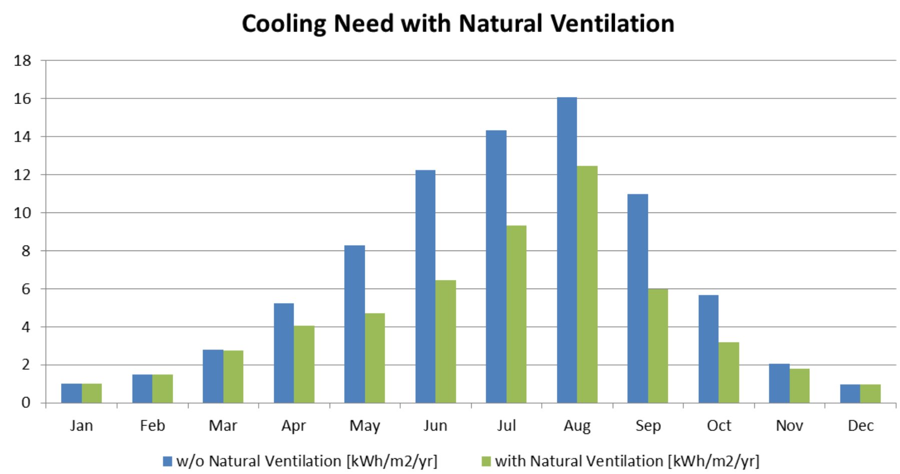


Figure 74. Monthly cooling demand saving: Alt-1

- **Alt 2**

Total available cooling hour for alt 2 is 556 hours which is about 21% of total operation hours. As shown on alt 1, the swing seasons June and September have longest hours for natural ventilation benefit. Because alt 1 has higher solar heat gain for internal cooling load than alt 2, available cooling hour of alt 2 is less than alt 1.

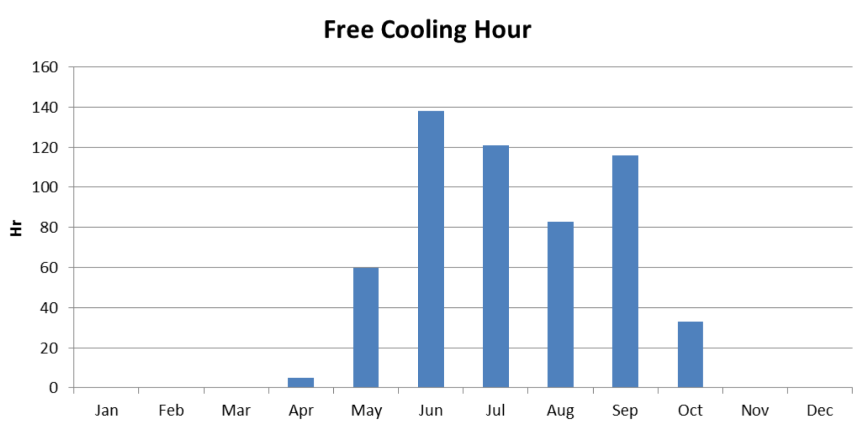


Figure 75. Monthly free cooling hour in Alt-2

The total saving in cooling load by natural ventilation is 14.9kWh/m^2/yr. and it is about 27% of calculated cooling load without considering natural ventilation benefit. With the free cooling benefit, total energy demand for alt 2 is reduced from 109kWh/m^2/yr. to 94.1kWh/m^2/yr. The figure76 shows the monthly cooling load differences with natural ventilation.

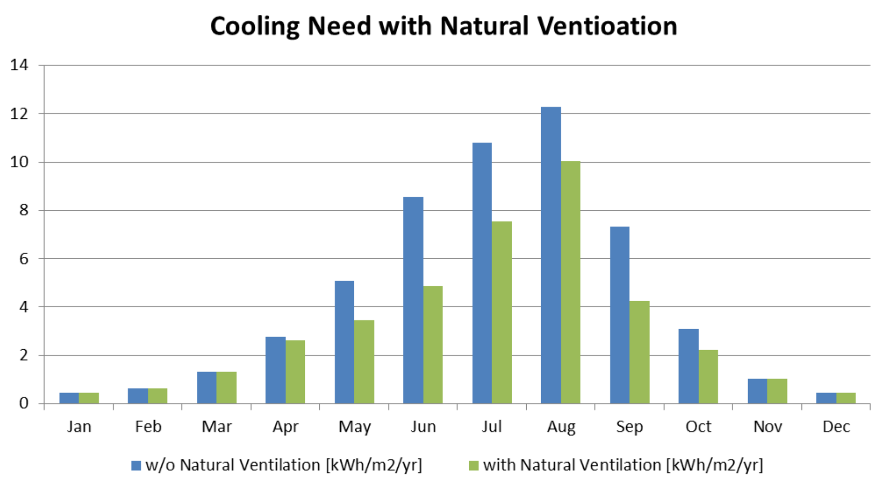


Figure 76. Monthly cooling demand saving: Alt-2

- **Alt 3**

Total available cooling hour for alt 3 is 506 hours which is about 20% of total operation hours, shortest time among 3 alternatives based on of its lowest internal load. As other alternatives June is the best month for natural ventilation and July and September are also have high available number when the humidity issue is ignored.

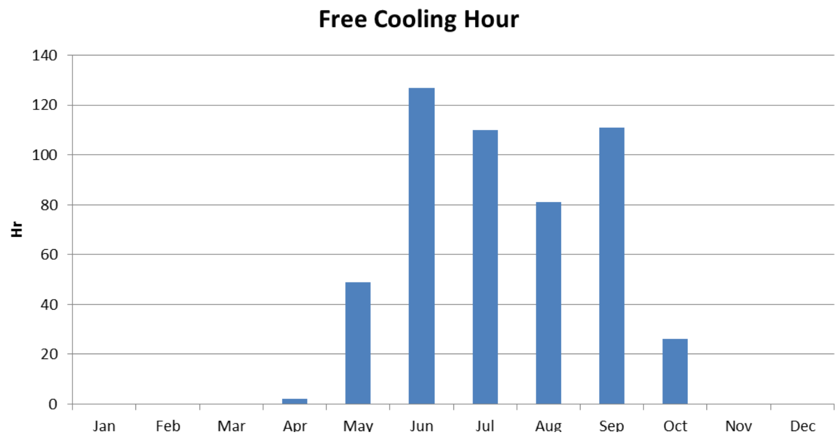


Figure 77. Monthly free cooling hour in Alt-3

The total saving in cooling load by natural ventilation is 12.75kWh/m^2/yr and it is about 30% of calculated cooling load without considering natural ventilation benefit. With the free cooling benefit, total energy demand for alt 3 is reduced from 84kWh/m^2/yr to 71.3kWh/m^2/yr. The figure 78 shows the monthly cooling load differences with natural ventilation in alt 3.

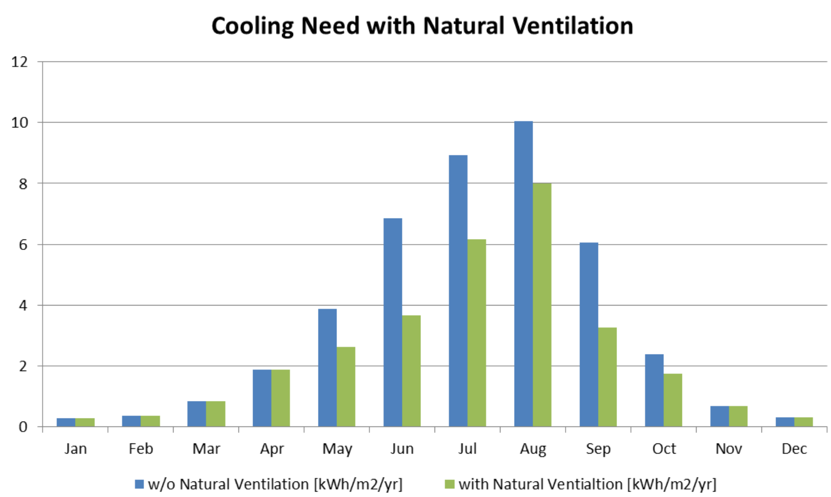


Figure 78. Monthly cooling demand saving: Alt-3

<u>Result Summary</u>

Because of the high solar heat gain through large glazing area, alt 1 has high internal load and it makes natural ventilation more feasible in this scheme. Although the available free cooling hours have some difference by each alternative, the total saving in cooling load is relatively similar to each other, about 30%. The possible energy saving with natural ventilation in this calculation shows good feasibility in application of the concept design. Although this estimation is good enough to compare schemes in early design stage, this estimation didn't consider the humidity and latent heat, so more detail study is required as design is developed. Moreover this study didn't consider the air filter to keep the pollutant particle out of space for indoor air quality. When the filters are applied, the calculated air change rate might be lower than the current number, and the air flow study need to be done again with new condition.

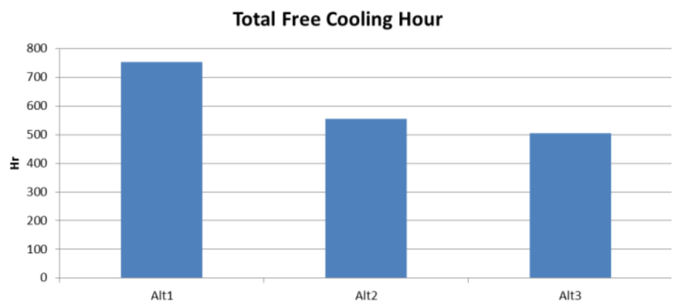


Figure 79. Total free cooling hour

Table 17. Energy saving by natural cooling

Total Energy Demand $kWh/m^2/yr$	Alt 1	Alt 2	Alt 3
w/o Natural Ventilation	125	109	84
w/ Natural Ventilation	**98**	**94.1**	**71.3**
Saving in Cooling (%)	**33**	**27**	**30**

DESIGN DECISION WITH MULTIPLE CRITERIA PERFORMANCE

Normalizing Result Values

Each performance indicator (PI) values should be normalized for comparing the 3 alternatives on a common scale. This case study used scale 0 to 1 and the normalized values are converted through the following process.

Table 18. Normalization of PI values

ID	Criterion	Units	Normalization (0 to 1)
PI1	Daylight Autonomy	%	Average DA in each floor × 0.01
PI2	UDI 100-2000	%	Average UDI in each floor × 0.01
PI3	Total Energy Demand	$kWh/m^2/yr$	The best performer value/ The value
PI4	Occupant view satisfaction rate	%	Value × 0.01
PI5	Available natural ventilation hours	hr	Available hour/Total operation hour

Performance based Decision Making

As described at the beginning of this chapter, each performance indicator represents the environmental impact of the building. Table 19 shows what environmental impact is are measured by each performance indicator.

Table 19. Performance indicator and environmental impact

	Criterion	Environmental Impact
PI1	Daylight Autonomy	Daylight Availability
PI2	UDI 100-2000	Visual Comfort
PI3	Total Energy Demand	Energy Performance
PI4	Occupant view satisfaction rate	Visual Connection to Outside
PI5	Available natural ventilation hours	Physical connection / Healthy IAQ

The normalized value for each design alternative is as Table 20, and it can be represented on radar chart, shown in figure 80.

Table 20. Performance criteria and PI values

	Criterion	Alt 1	Alt 2	Alt 3
PI1	Daylight Autonomy	0.91	0.9	0.82
PI2	UDI 100-2000	0.48	0.63	0.86
PI3	Total Energy Demand	0.72	0.75	1
PI4	Occupant view satisfaction rate	0.99	0.99	0.94
PI5	Available natural ventilation hours	0.3	0.21	0.2

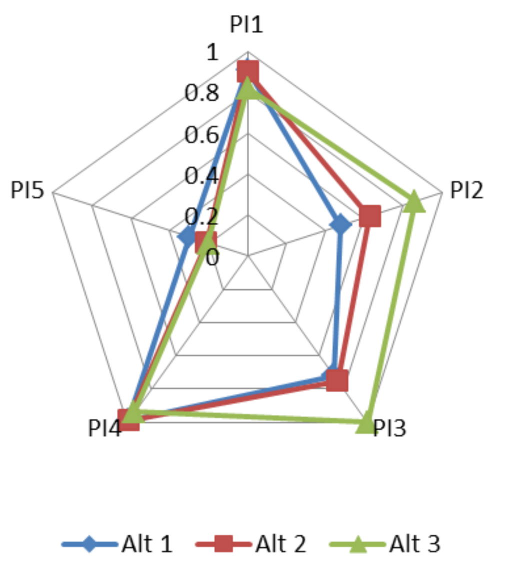


Figure 80. Normalized results

As seen on the graph, alt 3 shows the most competitive performance in all criteria. Based on the information provided by our performance study, the design team agreed to decide alt 3 for final design scheme to be developed. The next chapter shows how the selected concept design is to be developed for fabrication stage with material selection that considers sustainability based on life cycle assessment.

FABRICATION

Material Selection

Figure 81. HPL panel and Aluminum panel

Transparent and translucent gazing panels including mullion systems were selected based on their performance and project budget. The material choice for solid panels, however, was made in the consideration of environment impact as well as cost for construction and maintenance. There were two options; High pressure laminated (HPL) exterior panels [38] and Aluminum wall panels [37]. The criteria for comparison and their result values are as Table 21. The LCA information for both products is from the report by International Committee of Decorative Laminates Industry [36]. The LCA data are only regarding the 1mm surface sheet excluding the backup structure.

Table 21. LCA information for material options

ID	Criterion	Units	HPL	Aluminum	Data Source
PI1	Energy Consumption in LCA	MJ	83	350	LCA Report by ICDLI
PI2	Green House Effect (CO2 Emission)	Kg	6.0	23	LCA Report by ICDLI
PI3	Maintenance	US$/m^2	7	15	Local Product Data
PI4	Impact to Structure	Kg/cm^3	1.4	2.8	Product Data
PI5	Material Cost	US$/m^2	150	45	Local Product Data

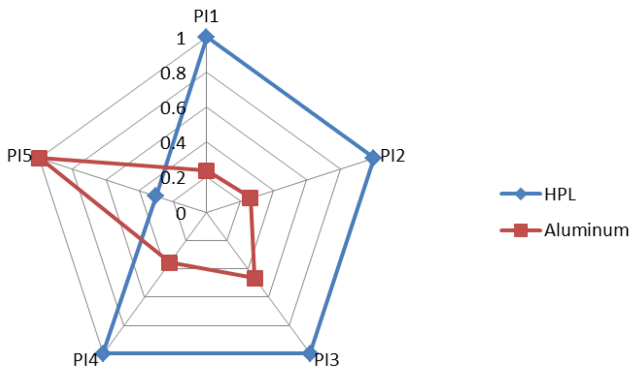


Figure 82. Normalized results: material selection

When the values are normalized as 0 to 1, the graph can be represented to compare those two products as figure 82.

As shown on the graph, the high pressure laminated panels have better performance in environmental impact and easy maintenance. Although the installation cost is about 3 times of typical aluminum cladding system, because the project scale and cladding area are relatively small, it doesn't make big impact on total project budget. The major exterior materials selected as below;

Table 22. Exterior material properties

	Type	Manufacture	Dimension	Properties	Sample Image
Glass	Low-e double glazing	KCC	24mm 12mm argon + 6mm clear	VT: 0.7 Emissivity: 0.29 SHGC: 0.39 U-Value: 1.25	
Translucent Panel	Super Insulating (R-20) translucent aerogel infilled	Kalwall	75 mm Thk, Max: 1.5m X 7.3m	U-value: 0.3 LT: 0.2	
Solid Panel	HPL Panel Glossy	Fundermax	8mm thk 2.8m X 1.3m	Conductivity: 0.3 Density: 1.45	

Detail Development for Fabrication

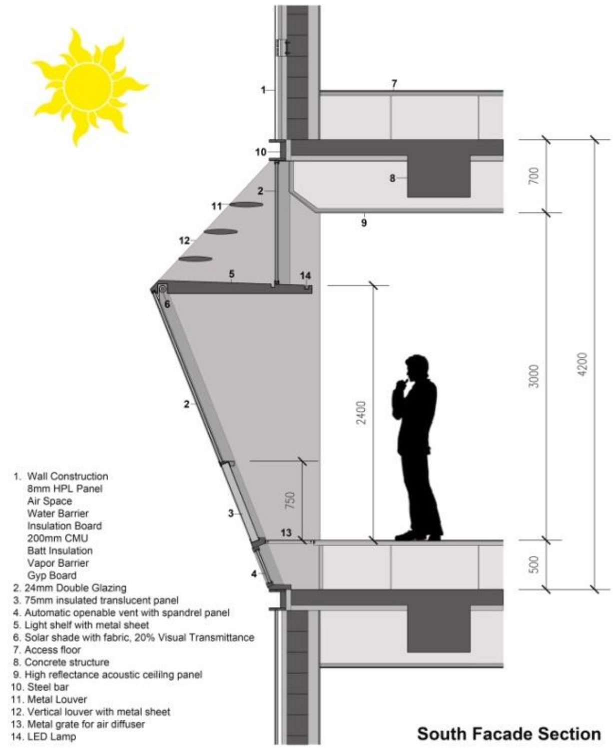


Figure 83. South facade detail section

After the major materials are defined, more detailed design to materialize the conceptual scheme with dimension is required. Although the exact dimension and details need to be verified by shop drawings of manufacturers later, it is important for the architect to understand how all building components should be assembled to perform as they are designed. Proper installation of insulation and water/vapor barriers is very critical to prevent unexpected performance failure through thermal bridging or condensation. To verify the required minimum dimension for installation of each building components can prevent unexpected design changes during construction, which usually can bring negative result in building performance.

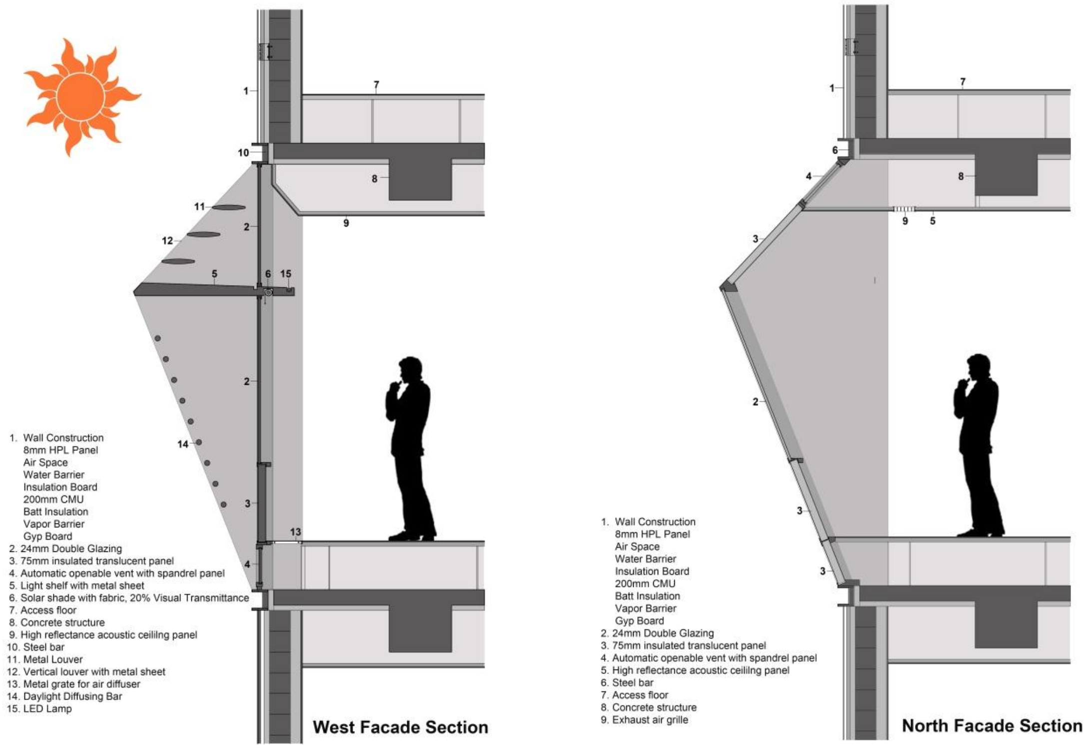


Figure 84. West and North facade detail section

Horizontal metal bar and vertical louver fin clearly divide the different modules. LED light strip is installed on edge of vertical louvers, which can be illuminated in night time to give accent on this building façade.

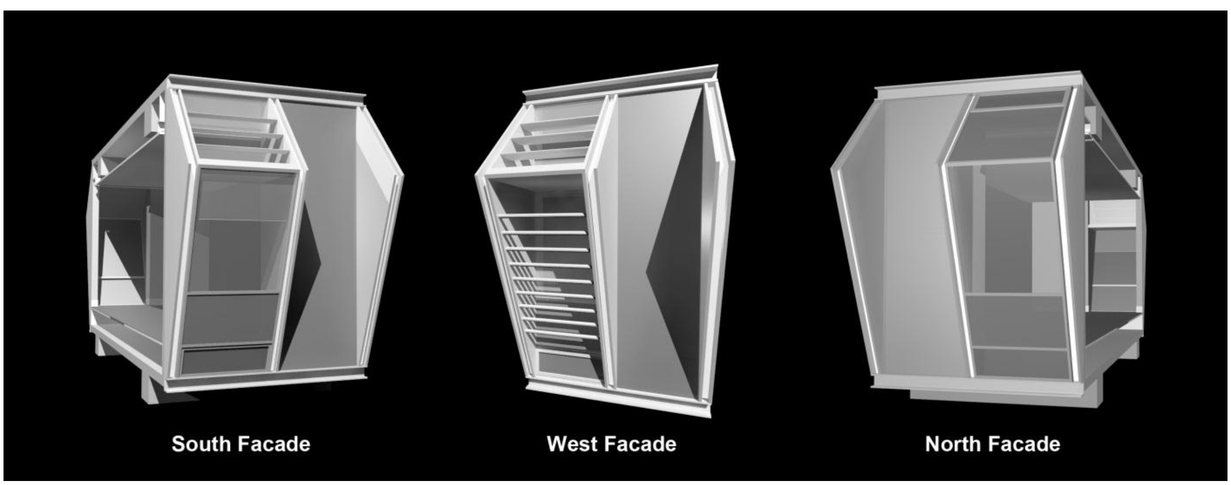


Figure 85. Digital fabrication for facade system

The following image is an expression of the building with selected façade alternative (alt 3)

Figure 86. Exterior image on site

CHAPTER 4

CONCLUSION

RECAPITULATION

Although the symbiotic relationship between design, function, and energy efficiency can be achieved by integrated mutual cooperation between designers and engineers, the limitation of resources, time, and cost, especially during early design phase, prevents it from being realized effectively in actual professional works. As the demand for high energy efficient building is growing, various building simulation tools are actively developed and some of them attract designer’s attentions. The tools, however, are mostly designed for engineers and researchers, and its use is often limited to validate building performances after design is completed. Tested and tried tools that can be used during early design phase are hardly available because of special requirements that the nature and working styles of early design poses.

This thesis presents the conceptual facade design process to satisfy various building performance targets in small scale office building with performance based integrated design method based on parametric design platform. The approach is based on clear statements of relevant performance criteria and their targets driven by expectations of client, design intents by architect, and local contexts including urban climate conditions and neighborhood aspects are prerequisite to keep the right direction during the design process. The criteria and their targets become the guideline to functionally decompose the building, which builds the relationship between functional requirements and systems to fulfill them. The analytical process regarding building function and its systems not only defines the parameters which need to control during parametric modeling process, but also helps to set up the indicators to verify the building performances.

A parametric modeling process with Grasshopper and Rhino was built to inspect the effect of relevant parameters to satisfy main design intents. Three façade design alternatives were generated by parameter variation driven by design intents. Each design alternative is verified for their performances by a range of selected simulation tools connected with the parametric modeling platform directly or indirectly, and parameter optimizations for each design alternative were done based on the simulation results as iterative loop process until to achieving the best combines performance. The PI (Performance Indicator) values of each performance criterion acquired from the process are compared for each design alternatives, which provides critical information to make design decision. The selected design needs to be re-verified with initial design intent and project performance target not to deviate the original design goal. After the conceptual design is confirmed, more developed design regarding material selections and fabrication details was done focusing on the satisfaction of sustainable design intent translated to LCA and maintenance cost.

The final scheme in the case study for small office building facade designed throughout the design process satisfied the original design target. According to the daylight simulation results, the indoor lighting level of the selected scheme satisfies IESNA recommended lighting level for office by only daylighting in excess of 80% of the year without compromising the visual comfort and thermal energy demand. The scheme showed very stable daylight levels without extremes, providing comfortable visual condition to occupants, during over 85% of the year. The building energy demand also showed a very promising number, 71kWh/m^2.yr, which is significantly better than current Korean national energy code requirement for the 1st degree energy efficient building certification, 100kWh/m^2.yr for office. Natural ventilation feasibility was also considered and the ventilation concept was verified with CONTAM simulation to check how much air volume can pass through the space when outdoor conditions are favorable to provide enough air to offer free cooling in the case building design. The natural ventilation can save 30% of the cooling demand in this case study. Material selections and construction details are also made under consideration of low environmental impact as well as convenient maintenance.

The results of all simulations are preliminary and conditioned on certain uncertain factors, they are reliable for comparative analysis and there is little doubt that the resulting optimal variant is indeed the variant that best satisfies the client requirements. The important message is that the chosen process allows architects to understand how design parameters affect building parameters during the design process. It shows a glimpse of a building design driven by integrated building performance assessments with proper objective and unbiased verification.

LIMITATION AND FURTHER STUDIES

Even though energy simulation tools can be effectively integrated with the design process, the naive designer will not achieve his goal without proper functional and system decomposition that is adequate enough to capture the matching of functions and systems, where adequate performance indicators can be identified at their interface. It is not hard to find design examples where building simulation tools are used not for objective design decision tools but for providing fancy diagram for attractive presentations of hand-picked outcomes for the competing alternatives. In most cases these outcomes have little meaning for true objective performance statements and can consequently not be linked to client expectations. Unfortunately, that practice is pervasive in the industry as long as architects are working for uninformed clients. It is, therefore, very important for the industry (clients) to clearly understand that when, why, and what kind performance targets should play a role in the design process. Right answers only can be acquired through right questions, and tool users are asked to be able to judge the reliability of the simulation results. A two-way transparent understanding of the dialog between expectations and fulfillment will become the solid foundation for healthy communication between designers and engineers in the performance based integrated design process.

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