A New Approach in Data Visualization to Integrate Time and Space Variability of Daylighting in the Design Process

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Abstract:

Daylighting design has great impact on the performance and aesthetical quality of a work of architecture but requires many issues to be addressed during the design process. The way existing daylighting tools deliver data to designers is still inefficient. The output display has no quick switch between quantitative and qualitative data and simply considers single moments with fixed weather condition. Designers are interrupted in their design process, and they usually need to make a data synthesis themselves, with the risk of overlooking critical periods or aspects of the design.

Therefore, this thesis proposed a new data visualization method to improve this situation and create a more efficient data transmission between the designer and the program to better inform and support the design process. It used some existing research work in progress and developed a functional data visualization platform to simultaneously present sufficient quantitative and qualitative data over the year while linking closely the performance to annual weather variations, sun positions, and surroundings. As a result, designers are able to focus on refining their design while still taking into account the environmental influence over time in a convenient way. The proposed platform will work as an analysis interface for the ongoing **LightSolve** project at MIT Daylighting Lab.

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TABLE OF CONTENTS

1 Introduction

1.1 Daylight in Architecture 9

1.2 Daylight as an Influencing Factor for Design 12

1.3 Structure of Thesis 14

2 Research Context: Data Visualization in Design Process

2.1 Architectural Design Process 16

2.2 Data Use in Design Process 17

2.3 Important Data Representations of Lighting and their Influence in Daylighting Design 18

2.3.1 Qualitative Representations 20

2.3.2 Quantitative Representations 22

2.3.3 Link between Daylighting Performances and the Changing Outside Environment 23

2.4 Data Visualization Study of Existing Lighting Simulation Tools 26

2.4.1 User Based Lighting Simulation Tools Comparison 28

2.4.2 Available Data Representations 30

2.4.3 Data Switch 32

2.4.4 Daylighting Performance and Outside Environment in Data Output 35

2.4.5 Data Output and Time Variation 37

2.4.6 Data Output and Design Goals 39

2.4.7 Comparison Summary 39

3 Thesis Research Method

3.1 Objectives of Thesis 41

3.2 Thesis Approach 41

4 Design and Development of an Data Visualization Platform

4.1 Concept of Proposed Platform 44

4.2 Interactive Data Browsing 48

4.3 Additional Simulation Methods

4.3.1 Annual Image Map 50

4.3.2 Simulation over Time and Date 52

4.3.3 Comparison Panel 53

5 Platform Validations

5.1 Case Study of Current Tools 56

5.1.1 Digital Model Preparation 58

5.1.2 Daylighting Analysis in 3Ds Max and Ecotect 63

5.1.3 Existing Problems ....
5.1.4 Data Visualization Comparison 76
5.2 Demo Museum Design Informed by Proposed Data Visualization Method
5.2.1 Initial Design 78
5.2.2 Design Improvement and Daylighting Analysis 88
5.2.3 Louver System Adjustment 95
5.2.4 Demo Design Discussion 99
5.3 Validation of Revealing Real Performance Issues 101
5.4 Validation Survey by Intended Users
5.4.1 Survey Results 107
5.4.2 Survey Discussion 109

6 Conclusion
6.1 Thesis Achievements 111
6.2 Future Work 112

Appendices
1: Material settings in 3Ds Max 8.0 for Yale Center for British Art Case Study 113
2: Material settings in Ecotect 5.5 for Yale Center for British Art Case Study 115
3: Material settings in 3Ds Max 8.0 for Stata Center Room 32-376 Case Study 117
4: Material settings in Ecotect 5.5 for Stata Center Room 32-376 Case Study 119
5: Validation 4 questionnaire 121
6: Validation 4 questionnaire results 123

Bibliography 124

Chapter 1

Introduction

1.1 Daylight in Architecture

"We were born of light. The seasons are felt through light. We only know the world as it is evoked by light …… To me natural light is the only light, because it has mood – it provides a ground of common agreement for man – it puts us in touch with the eternal. Natural light is the only light that makes architecture architecture."

-- ***Louis I. Kahn***

Daylight has always played a major role in architecture. It is one of the essential resources for helping people sensing the world of architecture [Brawne, 2003], and is a primitive source of illuminating people's activities to make the building more functional and revealing the shape of the building [Millet, 1996]. Light, especially daylight, is dominant in our sensation of form and space, and without light, any form and space equals nothing [Brawne, 2003]. Therefore, daylighting plays a significant role in the architectural design process as well. It also helps create particular visual effects and atmosphere for different building purposes [Baker, 1993]. From the very beginning in architectural history, a great numbers of architectural masterpieces were created by architects that were in fact driven by the idea of how to use daylight in their designs [Büttiker, 1994] [Guzowski, 2000].

"Until the second half of the twentieth century when fluorescent lighting and cheap electricity became available, the history of daylighting and the history of architecture were one." [Lechner, 2001] Because of the difficulty of getting cheap and efficient artificial light before the widely used electric lighting, getting enough daylight was one of the major objectives for architects [Lechner, 2001]. The building itself had to be functional by allowing people to perform indoor activities during the day, and it also had to be lit by daylight.

This idea contributed greatly to every architectural evolution. The goal of letting more natural light enter the buildings was reflected in the structural changes in these evolutions [Lechner, 2001] [Broadbent, 1988]. For instance, from the Romanesque barrel vault to Roman groin vault, a distinct change was to get rid of the massive bearing walls supporting the barrel vault and using columns with flying buttresses to support the vault instead (figure 1.1[1]). By doing this, the walls in the vaulted space were no longer used for supporting purpose. It became possible to increase the amount of daylight entering the building, because more windows with larger area were allowed on the walls rather than only allowed few small openings on the bearing walls for barrel

[1] All figures are produced by the author unless noted.

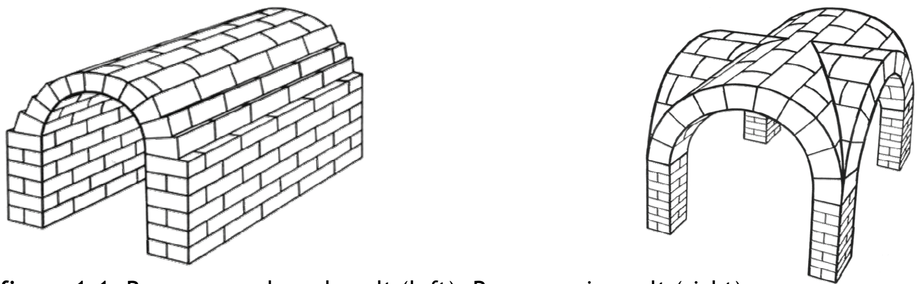


figure 1.1: Romanesque barrel vault (left), Roman groin vault (right).
www.uky.edu/Classes/A-H/323/restricted/terms.htm

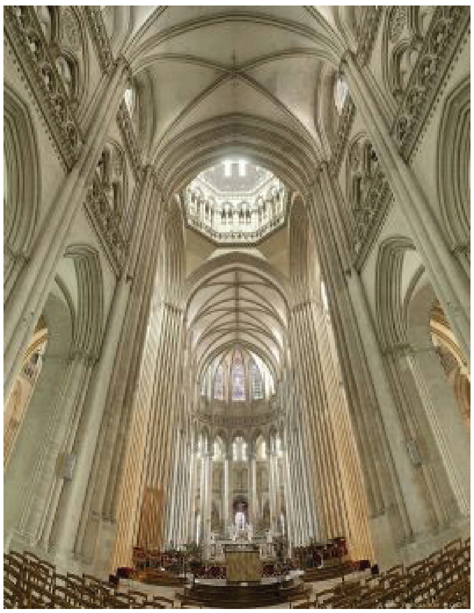


figure 1.2: Gothic architecture.
www.gargoylegothica.com/

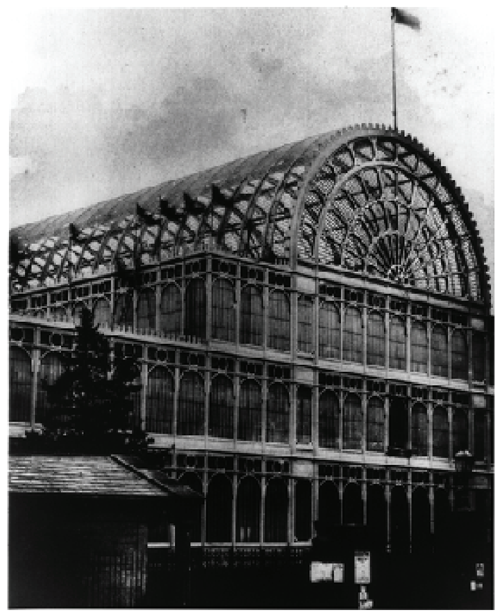


figure 1.3: Crystal Palace designed by Paxton, London. www.ric.edu/faculty/rpotter/cryspal.html

vault [Lechner, 2001]. Gothic architecture is another example (figure 1.2). Its major goal was to get more daylight in by maximizing the possible window area in its structure system. Its skeleton construction of the flying buttresses allowed build very large windows [Lechner, 2001].

During the period of the Renaissance, windows became a dominant element on the building's façade. The typical floor plans in that period basically followed the pattern of "E" and "H" because these types of design could increase the façade area for a given floor area [Lechner, 2001], hence, increase the window area. At the same time, high ceilings were used in combination with room depths about twice the floor to ceiling height so that every where was possible to get access to daylight [Broadbent, 1988].

In the nineteenth century, iron and glass structure was available for architects thanks to the industrial evolution [Broadbent, 1988] [Lechner, 2001]. Buildings with full glass skins became possible, such as the landmark design of the Crystal Palace by Paxton at London, built in 1851 (figure 1.3).

This trend continued in the twentieth century. The popular international style created by *Mies van de Rohe* was famous because of his use of iron and glass structures in skyscrapers (figure 1.4). Although it maximized window area in the façade and allowed daylight to come in freely, there was no control of solar heat gain and people found it very difficult to stay comfortable without blocking sunlight. The more difficult control of daylight made electric lighting became the preferred and major lighting source, while air conditioning became more and more popular to provide comfortable temperature [Lechner, 2001].

This situation was in great part caused by the cheaper and easily controlled electric lighting. People realized they could get the same amount of illuminance by simply using electric light without considering any details of the building orientation, openings, depth, and so on [Lechner, 2001]. Daylight was no longer the central element in architecture.

“The energy crisis of the mid-1970s led to a reexamination of the potential for daylighting” [Lechner, 2001]. People began to realize that daylight was still valuable because of its aesthetic effects and biological benefits [Guzowski, 2000]. Further more, many masters of architecture during that period, such as Frank Lloyd Wright and Louis Kahn, achieved perfect integration of daylighting considerations with their architectural design. In Wright’s Guggenheim Museum (figure 1.5), daylight is used “to illuminate the artwork both with indirect light from windows and with light from an atrium covered by a glass dome.” [Lechner, 2001]. The innovative geometry combining with this daylighting system creates a dramatic atmosphere. In *Louis Kahn*’s Kimbell art museum (figure 1.6), the use of skylight with a curved roof structure created a similar effect as the vaulted space and helped illuminate the exhibition room nicely [Büttiker, 1994].

figure 1.4:
Seagram building by *Mies van der Rohe*.
www.greatbuildings.com

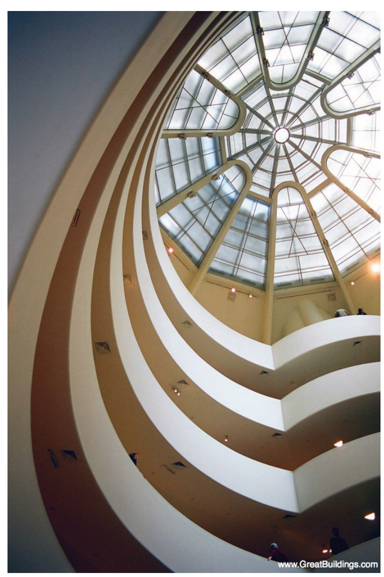


figure 1.5:
Guggenheim Museum by *Frank Lloyd Wright*.
www.greatbuildings.com

figure 1.6:
Kimbell art museum by *Louis Kahn*.
www.greatbuildings.com

figure 1.7:
National Capital of Bangladesh hostpital by *Louis Kahn* [Büttiker, 1994].

figure 1.8:
Pantheon in Rome.
www.greatbuildings.com

It is easy to find how daylight has influenced architectural design since the beginning of architectural history. This is revealed in the appearance of different architectural styles around the world according to different climate conditions [Lechner, 2001] in how visual effects are produced in the buildings [Brawne, 2003], in how energy efficiency considerations are brought in, and how health issues of the building's users have influenced design factors [Guzowski, 2000].

1.2 Daylight as an Influencing Factor for Design

Daylighting has deeply influenced architecture throughout history. In the National Capital of Bangladesh hospital (figure 1.7) designed by Louis Kahn, the innovation of using solid walls to create "double skins" was driven by the idea of blocking and diffusing direct sunlight caused by Dhaka's low latitude and motivated by prevention of solar gain and glare issues [Büttiker, 1994] . In the Pantheon in Rome (figure 1.8), solar movement helps to form the dimension of the hemispherical dome and its decorations [Fontoynont, 1999]. In Alvar Aalto's Seinäjoki Library (figure 1.9), the orientation of the skylight monitor was determined by the sun's azimuth while the geometry of its shading systems was based on the sun's altitude during the summer and winter [Guzowski, 2000]. All these examples reveal a strong relationship between design parameters and lighting parameters.

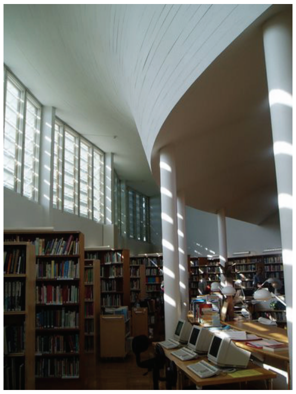


figure 1.9:
Seinäjoki Library by Alvar Aalto.
picasaweb.google.com/Dasulele/Vaas
a4Week

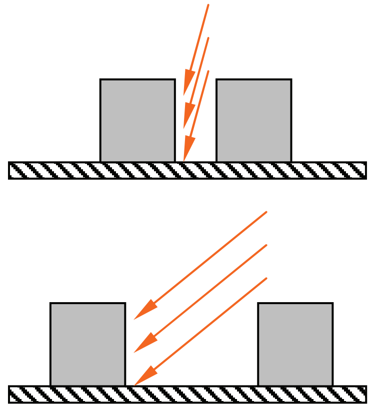


figure 1.10:
Relationship between sun angles and the building distance.

The most important design parameters in terms of daylighting are building orientation, geometry, position and size of apertures, shadings, and materials used in walls and glazing. These decisions will influence lighting performance which is assessed based on the building's required illuminance level and desired lighting atmosphere. We can create a mapping between the building's functionality, a design parameter, to the required illuminance level, the corresponding lighting parameter. A working area in an office building typically requires an illuminance of about 300 lux illuminance level to provide adequate lighting for people to read and write, while the entrance of the same office building would only need an illuminance of about 100 lux.

Local environmental factors, such as latitude of the location, weather conditions, sun angle ranges, etc, also have a great impact on these decisions. For example, the latitude of the location can greatly affect the direct sunlight entering into the interior space. When the building is located at low latitude with high sun angles, the distance between building and its surroundings and the distance between different parts of the building can be short while still allowing sunlight to come into the interior space (figure 1.10). This is not true at high latitude, when the sun is normally low; these distances always have to be long enough to allow sunlight to penetrate (figure 1.10). Hence, the buildings orientation and geometry have to be designed to response this attribute of its location. Weather variation is also needed to take into account in many cases. Because under an overcast day, only diffuse daylight is available, while under a clear sky the major contribution of the natural light is the direct radiation. This variation sometimes caused entirely different design of the same type of projects [Guzowski, 2000]. Therefore, the architectural design is needed to consider this variation as well.

The above discussion reveals a strong influence of these daylight factors in the building's performance. It clearly shows that it is necessary to integrate daylighting considerations into the architectural design.

1.3 Structure of Thesis

The structure of this thesis is organized based on the design and development of a new data visualization method and a functional platform implementing the proposed method.

In Chapter 2, it discusses the data visualization in the architectural design process in terms of daylighting and what data representations are important and have to be delivered to the designer to support him comprehensively evaluating the daylighting performance and making appropriate design decision. In addition, it studies the data visualization process of existing lighting simulation, how they inform and support the design process, and what their data visualization limitations are.

In Chapter 3, it presents thesis's objectives of creating a new method for data visualization focusing on daylighting, simultaneously displaying various types of information, and conveniently accessing data over the whole year. In addition, it mentions that this method uses existing research work, the quantitative temporal map being developed at MIT Daylighting Lab, as the major quantitative data output, and it also uses the concept of the render engine being developed at RPI Department of Computer Science, as the way to quickly produce qualitative rendering outputs. It introduces that a platform is developed to implement the proposed method and will work as an analysis interface for the ongoing **LightSolve** project at MIT Daylighting Lab.

In Chapter 4, it presents the design and development of the data visualization platform implementing the proposed data visualization method and introduces the main features of the platform and other simulation methods.

In Chapter 5, it presents four validations of the proposed method. The first validation is a case study that analyzes existing buildings in two current tools. It then discusses their limitations and makes a comparison between them and the proposed platform. The second validation tests whether the proposed method can inform and support better the design process. A demo museum design is developed under the influence of the proposed data visualization platform. The third validation tests whether the proposed platform is able to reveal the real performance issues. It presents the interview to the space user at Stata Center Room 32-376 and the analysis result displayed in the platform. The fourth validation platform is a survey to architectural students. This validation tests whether the platform is intuitive and useful from these intended users.

Chapter 6 is the conclusion of the thesis. It summarized the major achievements and research discoveries. In addition, it also discussed the possible future work and potential research beneficiaries of the thesis production.

Appendices 1 and 2 presents the material settings of the digital model for the Yale Center for

British Art in AutoDesk 3Ds Max 2009 and Ecotect 5.5 in Chapter 5’s first validation.

Appendices 3 and 4 presents the material settings of the digital model for the Stata Center Room 32-376 in AutoDesk 3Ds Max 2009 and Ecotect 5.5 in Chapter 5’s first validation.

Appendices 5 and 6 present the questionnaire and its survey results for the validation test 4.

Chapter 2

Research Context: Data Visualization in the Design Process

2.1 Architectural Design Process

Architectural design process is usually being described as a non-linear process that cannot be quantified easily; however, there are still constant drivers that motivate the design as it moves toward its final iteration. The architectural design process can be considered as a process of creating forms and spaces [Broadbent, 1988].

The design process can be described as a sequence of steps [Broadbent, 1988]:

1) accumulation of data
2) isolation of a general concept or 'Form'
3) development of the 'Form' into the final scheme
4) presentation of the final scheme

In the first step, the designer will gather various types of information, such as the function of the project, the client's needs, the potential space users, the requirement of the building's area, the urban context, etc. Information of previous designs which have been known by the designer may also be presented in his mind as a database of possible design solutions for this topic.

After an architect accumulates data in the first step, he is able to formulate an initial design concept, and a list of basic design possibilities and design constraints becomes clear in his mind. Most architects will begin their creation by a series of conceptual drawings (figure 2.1) based on that list. This process of creating initial conceptual drawings corresponds to the second process, the isolation of a general concept or 'Form'. As is argued in Michael Brawne's "Architectural thought: The Design Process and The Expectant Eye" [Brawne, 2003], "Architecture thought is primarily non-verbal thought …… Visual thinking is particularly relevant at the design stage which is also the stage in which an architect makes the most significant impact." Architects always begin their design by images either on paper or in their mind. Those conceptual drawings have already contained the architect's initial thinking of function, lighting, structure, etc, and they are mainly sketches which are simply composed by black marks on white paper.

The third step, the development of the 'Form' into the final scheme, is the major part of the architectural design process. In fact, this process cannot be considered as only one step when we look at it on a deeper level, because it contains a loop of the 'Form' development. In this

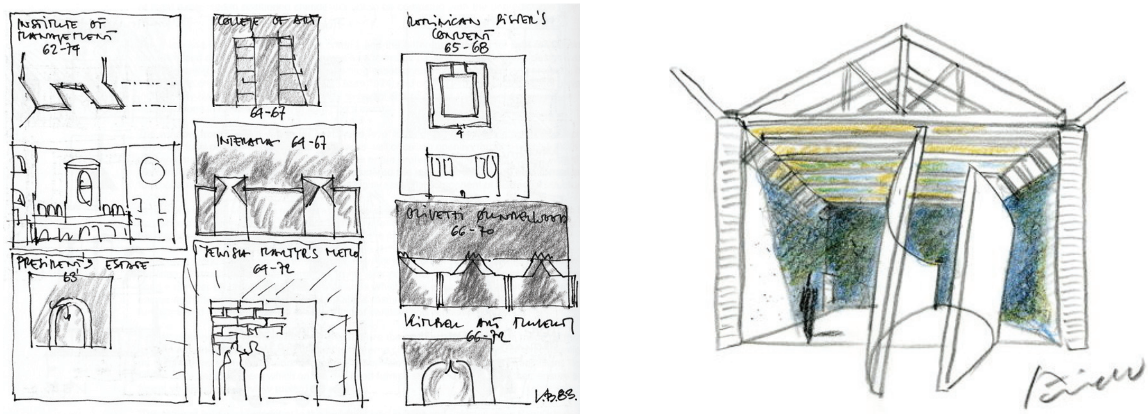


figure 2.1:
Conceptual sketches by Louis Kahn (left) [**Büttiker, 1994**] and Tadao Ando (right, www.arkitectrue.com/arts-centre-by-tadao-ando/).

development, the designer follows the typical trial-and-error process to first evaluate his design and then perform experiments on refining the geometry and adding more design detail. These evaluations may reflect the consideration from many different perspectives, such the aesthetic consideration which is a very important criterion in architecture, the lighting effect, the structure system, etc. They can be entirely based on the designer's own design goal, his personal experience, and works he is familiar with. They may also be based on professional calculations provided by consultants he is working with or by some computer simulation programs. From these evaluations, the designer may realize his design experiment may not work well within some basic design constraints and may raise some new constraints. He would search for other possible solutions and implement them in the next experiment. Until the architect reaches to the perfect moment, the images of the building in his mind will keep changing in every possible direction and keep moving from simpleness and vagueness to complexity and accuracy. In the final step where all the design decisions have been made, the designer will prepare final drawings and presentations for future construction.

2.2 Data Use in Design Process

The designer formulates the basic concept and design goals he would like to achieve based on the information he accumulates in the first step. For example, the urban context may become an important criteria to determine the orientation and the basic geometry; the function of the building may tells the designer how much space is needed for transportation and how much space is needed for individuals to work inside; previous works may reveal him possible lighting effect he could get in this design.

In the trial-and-error process during the third step, the design refinements are mainly informed by the information from every evaluation, therefore, the smoothness of the data delivery between the designer and these evaluations becomes crucial for this design process. The inefficiency data transmission can also effect the design process. It can cost too much time for the designer to collect them, and as a consequence, interrupt the design process greatly. Some important information may have a dangerous of being neglected because it is very inconvenient to obtain it. Therefore, this inefficiency greatly interrupts the designer's interpretation of this information and makes him impossible to make comprehensive evaluation and concentrate on the design exploration itself.

In sum, plenty of information is needed to be collected and delivered to the designer during the design process. They deeply informed the design process and play a significant role in supporting the design decision making. To keep the data transmission process smooth enough would be helpful to let the designer put all his attention on the design itself and make good final production.

2.3 Important Data Representations of Lighting and Their Influence in Daylighting Design

As discussed in Chapter 1, daylighting has a great impact on the building's lighting performance as well as the architectural design process. Lighting, especially daylighting, influences the design process since the early design stage. The design is influence deeply by many elevation results including the information of daylighting evaluations. However, "the sun never knew how great it was until it struck the side of a building" said by Louis Kahn [Johnson, 1975], it reveals this highly unpredictable property of light, especially daylight. Hence, it is crucial to have some efficient, accurate, and comprehensive way to assist the designer to evaluate the space's daylighting performance so as to smooth the trial-and-error process and help the designer making appropriate design decisions in terms of daylighting.

In order to better understand the daylighting performance of a design, different data representations need to be obtained and evaluated. Qualitative data, such as hand sketches or pictures from physical scale models (figure 2.1, 2.2), are well known data representations that have been widely used by architects to evaluate the visual effect of the space in the architectural design centuries ago [Brawne, 2003] [Baker, 1993]. Because of the rapid development of computer technology, computer renderings (figure 2.3) have begun to play an important role as available qualitative data for the prediction of the visual effect with increasing speed and flexibility of handling the repetition of remodeling parameters during the design process. To make the evaluation of a daylighting design comprehensive, the designer needs to obtain sufficient quantitative data to test whether the lighting condition of the space meets its function requirement [Brawne, 2003] [Fontoynont, 1999]. Interior illuminance level distribution and daylight factor distribution (figure 2.4) are the most common examples of quantitative data used by designers and the lighting professionals [Reinhart, 2006]. Getting enough qualitative and quantitative data and to evaluate daylighting performance is helpful for making appropriate design decisions; however, the understanding of the link between the outside environment and

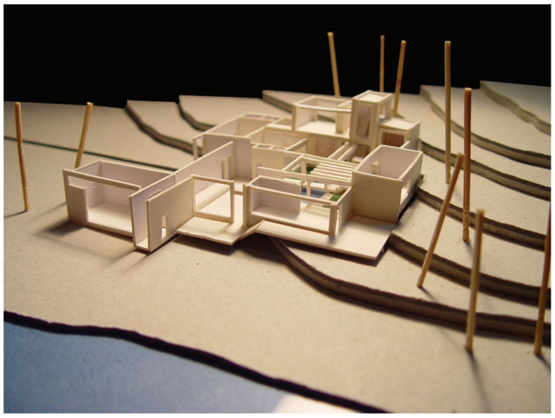


figure 2.2:
Physical scale model for a housing design, 2002

figure 2.3:
Computer rendering by Art-Lantis for a housing design, 2005

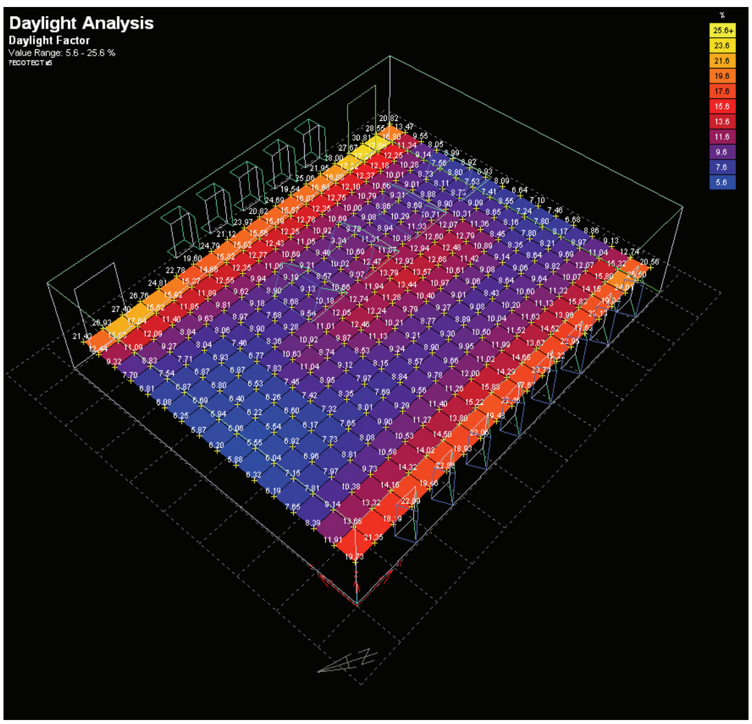


figure 2.4:
Daylight factor distribution at the work plane level of a classroom by Ecotect, 2007

the space is also very important to lead the design in the right direction and help find appropriate solutions to some daylighting problems. The quantitative and qualitative data tell the designer what the space's performance under certain conditions is, while the information of the outside environment, such as the sun position, sky conditions, and the surroundings, can reveal why the space interacts with light in a particular way [Guzowski, 2000]. Creating a seamless transmission of information between the designer that neither interrupts nor artificially sequences the design process but rather supports it comprehensively is crucial for a design tool to be successful.

2.3.1 Qualitative Representations

Qualitative visualization of space has a long history that dates back to the very beginning of architecture. Before the invention of rendering techniques, hand sketch and phyical scale models were a major resource for design visualization [Baker, 1993] [Ander, 1995]. They are still primary design tools nowadays, even though computer rendering is becoming more and more popular in today's design field. Hand drawings provide the designer an opportunity to freely describe the visual thinking process which happens in his mind [Brawne, 2003]. Great amounts of evidence on how hand sketches (figure 2.1) can support and influence the architect's thought process can be found in the works of many famous architects, such as Louis Kahn, Alvar Aalto, and Le Corbusier. In Kahn's work, we can find many hand sketches that describe his initial design ideas and the lighting effect he was looking for in these projects [Büttiker, 1994]. Some of them are simply line drawings with black and white indicating shadow and brightness (figure 2.5), some other sketches contain more gradual color between black and white to represent the diffuse effect of the space (figure 2.1, 2.6). The hand sketches often represent the designer's initial design goals related to lighting, especially daylighting. When the design process goes to the next step, the designer needs more visual information with a precise description of the space. Hand sketches no longer fit this requirement, since it is hard to dynamically display the view of the building from different perspectives using a hand sketch while the whole geometry is changing at the same time. Other tools, such as physical scale models, then become necessary and powerful tools to obtain qualitative data for the architectural design [Baker, 1993].

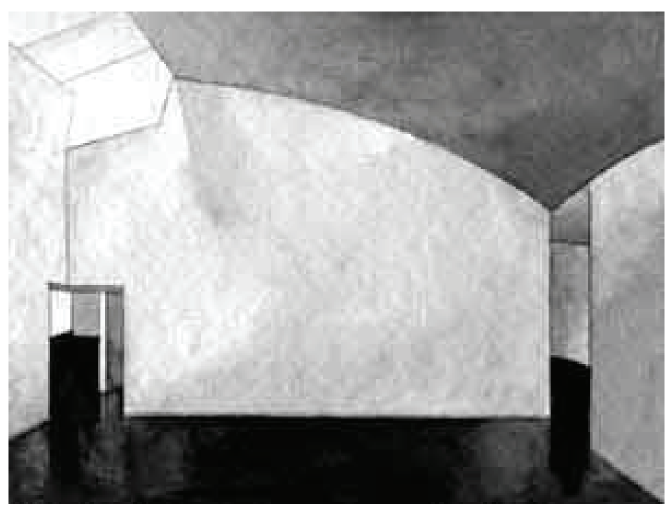


figure 2.6: hand sketch by Steven Holl for Museum of Contemporary Art Helsinki, Finland. www.arcspace.com/studio/s_holl/pages/9_jpg.htm

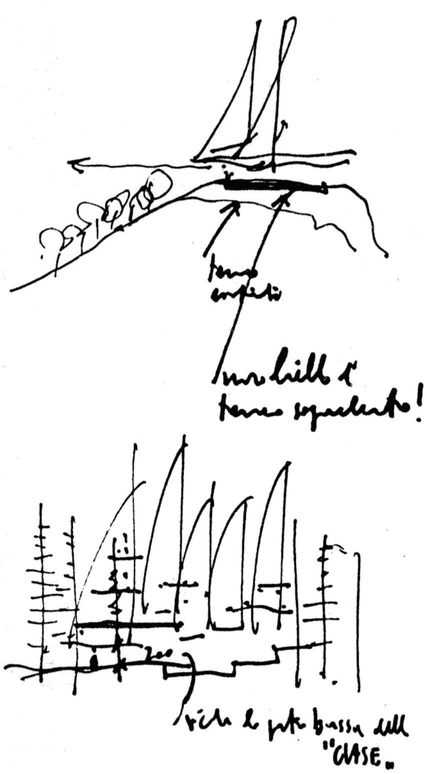


figure 2.5: hand sketch by Renzo Piano for Jean Marie Tjibaou Cultural Center, New Caledonia, 1992 [Lampugnani, 1994].

figure 2.7: Physical scale model used for a simulation test of the light shelf, 2007.

Compared with two dimensional drawings, scale models provide a different way to present accurate three dimensional information of a design before the actual building is built [Baker, 1993] [Ander, 1995]. One of the great advantages of physical models is that the designer can easily obtain visual information from any possible view for the design by simply rotating the model. It is very helpful during the design process, when the designer needs to go back and forth to refine his design from every crucial perspective and make sure to have harmony among different parts of the design. By choosing materials of appropriate dimensions and of colors similar to the ones intended for the real building, the physical scale model can provide a reliable lighting simulation of the space (figure 2.7) [Baker, 1993] [Ander, 1995].

On the other hand, digital models and computer renderings have become widely used in the architectural field. Nowadays, as is the case with physical scale models, digital models can easily provide views from any perspective; it also provides a much more flexible way of remodeling the design and updating visual information from computer renderings at any stage during the design process. Thus, computer modeling and rendering tools have become a very important resource today to provide qualitative data for design. All these tools help the designer to gather enough qualitative data to reveal the visual effect of the space and support the designer to make appropriate design decisions.

2.3.2 Quantitative Representations

Unlike qualitative data, which tells the designer what the space looks like from a visual perspective, the quantitative data represent the space's performance from a numerical perspective. It provides precise numerical values that represent different levels that can be switch to the visual information displayed in the qualitative data [Baker, 1993].

Illuminance indicates how much light that a particular area receives based on the amount of energy the light brings, and the human's sensitivity to the wavelengths contained in the light. Its unit is the lux (or lumen per square meter). The illuminance value is higher when more light is coming in. Generally speaking, spaces with different functions have various lighting requirements and are given in the table 2.1 shown below. The actual required light level for particular person may be higher or lower depending on his own condition and the surrounding environment. (Research has shown that the required lux level for certain activities is lower when using daylight, as compared to using artificial light.) Therefore, obtaining illuminance levels and light distribution within the space can help the designer to evaluate whether his design fits its future function. Simply having qualitative renderings is not enough for designers to make such estimation when the quantitative data is missing.

Lighting Requirements	Lux	Examples
Low	20-70	Circulation, Stairs
Moderate	120-185	Entrance, Restaurant
Medium	250-375	General tasks
High	500-750	Reading, Writing
Very high	> 1000	Precision tasks

table 2.1

Daylight factor (figure 2.4) is a metric widely used in daylighting design. It calculates the ratio of the illuminance level obtained at a certain point inside the space to the illuminance level obtained at an outside point with no obstruction and under an overcast sky. Because it selects an overcast sky as its tested weather condition, it is a worst case scenario evaluation that simply considers diffused daylight from the sky as the major light source and neglects direct sunlight. In this case, the orientation, the climate, the location, and the time are not taken into account. It is however able to give a quick idea to the designer of how much impact certain design decision will have on the performance, such as position and size of openings and material selections, etc. The LEED system used it as determining criteria to assign daylighting credits to a building (Projects with 75% areas having over 2% daylight factor could obtain 1 credit for daylighting in LEED version 2.1).

Daylight autonomy is another quantitative metric for daylighting evaluation [Reinhart, DAYSIM, 2006]. Unlike the daylight factor, which is a static metric considering an overcast sky without including orientation, climate and time variation, daylight autonomy is a dynamic metric that addresses the change in weather over the year [Reinhart, 2006]. It calculates the percentage of working hours when a minimum work plane illuminance is maintained by daylight alone. While the daylight factor metric is available in many lighting simulation tools' quantitative output, daylight autonomy is a new metric being produced by DAYSIM and now integrated into Adeline, and emerging as a default alternative.

Distinct from illuminance, which indicates how much flux a surface receives, the luminance metric describes the amount of light the surface emits in a given direction. Achieving a harmonious luminance distribution is crucial in daylighting design. Unevenly distributed luminance values can cause serious glare problems that might disturb people's work, such as reading, writing, and using the computer. Therefore, buildings like schools, offices, and labs have to have careful control of glare to make sure people's everyday work will go smoothly.

From the discussion of qualitative and quantitative data, it is apparent that qualitative hand sketches and renderings tell the designer what the space looks like, but it cannot indicate whether the lighting level in this space meets its function. Quantitative data are able to provide comprehensive description of how much light the space can get and emit; however, quantitative data poorly describes the way how light interacts with color, shadow, and the building geometry. In daylighting design, both qualitative and quantitative data are necessary and crucial information for the designer to evaluate the daylighting performance of the design.

2.3.3 Link between the Daylighting performance and the Changing Outside Environment

Qualitative data helps to visualize an architectural design while quantitative data helps to validate whether the lighting condition meets the requirement for particular functions. Both of them describe the daylighting performance of the space. However, even their combined knowledge is still not quite enough to make appropriate daylighting evaluation and design decisions, since it is also crucial to know the circumstances under which this particular daylighting performance happens. Understanding the link between the performance and the environment that drives this performance is then necessary to make appropriate design improvement.

As Guzowski argued in "Daylighting for sustainable design" [Guzowski, 2000], "The track of the sun, the conditions of the sky, the climate, and the nature of the site are significant bioregional forces that influence daylighting". Although the building's own characteristics such as the orientation, geometry, opening's position and size have a great impact on how daylight interacts with the space, the outside environment is the major important predetermined factor (although not always well known and definitely not controlled) influencing the interior daylighting performance of a building.

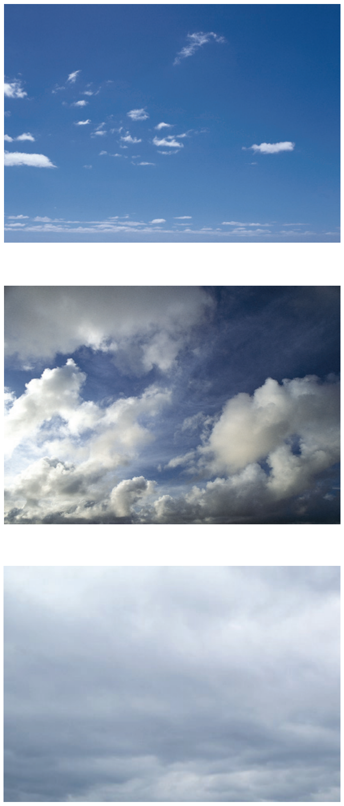


figure 2.9: different sky conditions: clear (top), partially cloudy (middle), and overcast (bottom).

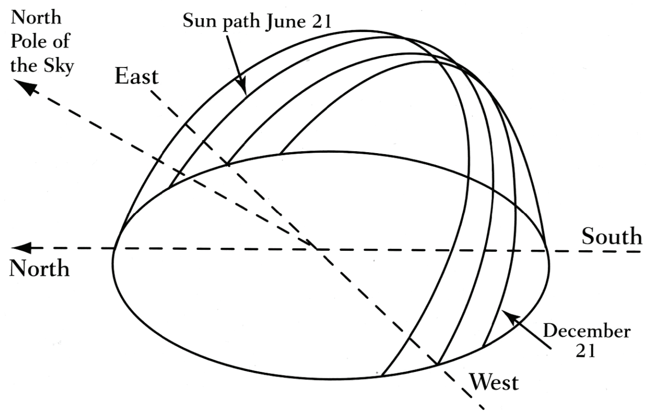


figure 2.8: The path of the sun is different over the year [Winchip, 2005].

Sun position is the major factor that influences how direct sunlight can penetrate the building and create shadow [Guzowski, 2000]. Sun position varies according to location and time of day and year (figure 2.8). In the northern hemisphere, we get deeper sunlight penetration early in the morning from an east-facing window and late in the afternoon from a west-facing window. It also brings longer shadows during the winter than during the summer.

Having an understanding of sunlight variation over time of day is critical when doing daylighting design. The designer should ensure that the building can benefit from the direct sunlight resource at certain times of day at that particular location. Although looking at the renderings or quantitative analysis metrics is able to tell you a west facing room in the northern hemisphere is dark in the morning, the designer has to do research on the sun movement so as to understand what causes this performance in the rendering. In this case, changing the orientation of the façade or adding openings on the east façade may have greater impact on improving the illuminance level of the space than increasing the opening size on the west facade. Hence, linking the sun position with the qualitative and quantitative data is helpful for the designer to figure out the reason of the problem.

In addition, sky conditions (figure 2.9) are another important environmental factor that influences interior daylighting performance. Natural light has two components: one is the direct radiation from the sunlight, the other one is the diffuse radiation from the sky [Baker, 1993] .

Under clear skies where there are no clouds, the sun is the brightest with the bluest sky color. The diffuse radiation from the sky itself only takes 10% to 20%. Under an overcast sky, the situation is at the opposite extreme; the diffuse radiation becomes 100% with no direct radiation from the sun and the sky becomes grey. Thus, the sky has different illuminance distributions under different weather conditions. In this case, to explain why the space has certain daylighting performance at particular location and time has to take into account not only the sun position but also the sky condition at that moment. Although some location have similar latitude and longitude, if they have entirely different weather patterns over time, they may still need to use different designs to achieve the same daylighting performance requirement [Guzowski, 2000]. Therefore, knowing the sky condition at a certain moment and the sky condition distribution over the year is also crucial for the designer to improve his design and better adapt it to the climate at a particular location.

Furthermore, the physical surroundings of the building may have a significant impact on the daylighting performance [Guzowski, 2000]. The relative position of the surrounding to a building, the distance between the surroundings and the building, and the surface properties of the surroundings are all important factors that affect how much and in what way light comes into the building (figure 1.10). Sometimes, although the surrounding's position and distance is appropriate for the building, it has a large area of reflective façade facing the building so that the building is still suffering great glare problems from it as was the case of Frank Gehry's Disney Concert Hall in Los Angeles (figure 2.10). As a result, the designer has to consider the possible effect of the surroundings on daylighting performance and develop his design to fit the urban environment.

figure 2.10: Walt Disney Concert Hall, Los Angeles, CA, USA, designed by Frank Gehry.
www.terragalleria.com

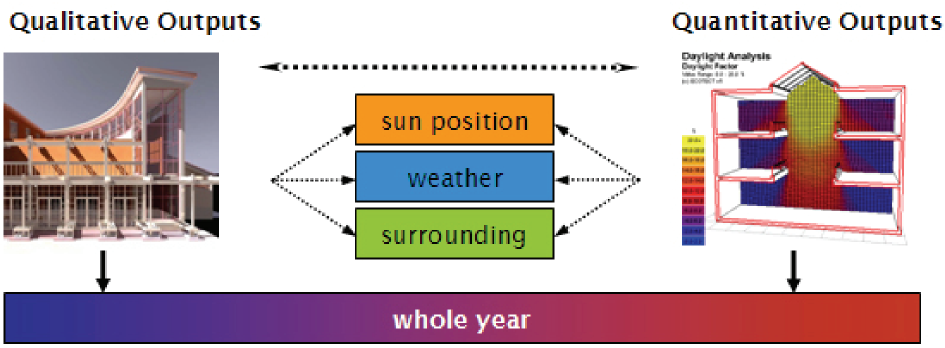


figure 2.11: Important data representations in terms of daylighting design and their relationship

Since all the environmental factors discussed above are not static over the year, looking at daylighting performance for individual moment in time is not enough to demonstrate the quality of the daylighting design and find potential problems. The design that works well with low sun angle direct sunlight may perform badly during noon time or under an overcast sky. To make sure the building is able to respond with the variation of these daylighting environmental factors, the designer has to explore the performance over the whole year. This is the only meaningful way a designer can understand the underlying annual variation patterns of the sun position, sky condition, the surroundings and how the space interacts with these variations.

In summary, developing an appropriate daylighting design requires the designer to obtain enough qualitative and quantitative data simultaneously to understand the daylighting performance and corresponding outside environmental information that has an impact on the interior performance (figure 2.11). In addition, it is crucial for the designer to examine annual variations in daylighting rather than a set of static moments under fixed weather conditions. Creating such a data transmission method that successfully delivers these daylighting data during the design process will be helpful to inform the designer and assist him in refining the design in a more appropriate direction.

2.4 Data Visualization Study of Existing Lighting Simulation Tools

Before making any design decisions, a designer will usually run some tests to get a sense of whether his design solution performs according to his initial design goals. He then (typically) resorts to some tool that can help perform these evaluations in advance to see if further modification is needed or not. In this case, the physical scale model has been a popular design tool in the architectural field for centuries, because it helps visualize the shape of the building and provide an exploration platform for the architect to develop the design from a schematic stage to detailed levels. It is also an excellent tool for the lighting study of the building (figure 2.7) [Broadbent, 1993].

However, there are still some limitations for physical scale models. In the architectural design process, there is always a repetition of evaluating a design solution, revising it if necessary, and going back to the beginning to test it again. It is clearly inconvenient to rebuild a physical model every time in this sequence. At the same time, some materials cannot be scaled easily, although it is easy to scale the geometry. This can cause lighting related quantitative measurements to be inaccurate [Broadbent, 1993]. The rapid development of computer aided design tools provides the designers with an efficient alternative to scale models. In computer simulation tools, the designer can easily change the digital model of his design and run lighting simulations by giving sufficient details of the geometry and the material under an appropriate sky model. Many programs like Radiance and LightScape can provide precise quantitative lighting analysis and realistic visualizations of the space (figure 2.11). From the web – based survey held from December 2nd 2003 to January 19th 2004 which focused on the use of daylight simulations in building design [Reinhart, 2006], an increasing interest in using computer simulation tools to support lighting related design issues has been found. In this survey, around 79% of all respondents including designers and engineers as well as researchers who indicated their consideration of daylighting during the design process used computer simulation tools (the survey itself has made through an electronic mailing list which many participants have biased the result according to the authors). On the other hand, one former mail-in survey in 1994 [Aizlewood, 1994] showed that 77% of daylighting specialists still used scale models as their simulation tools.

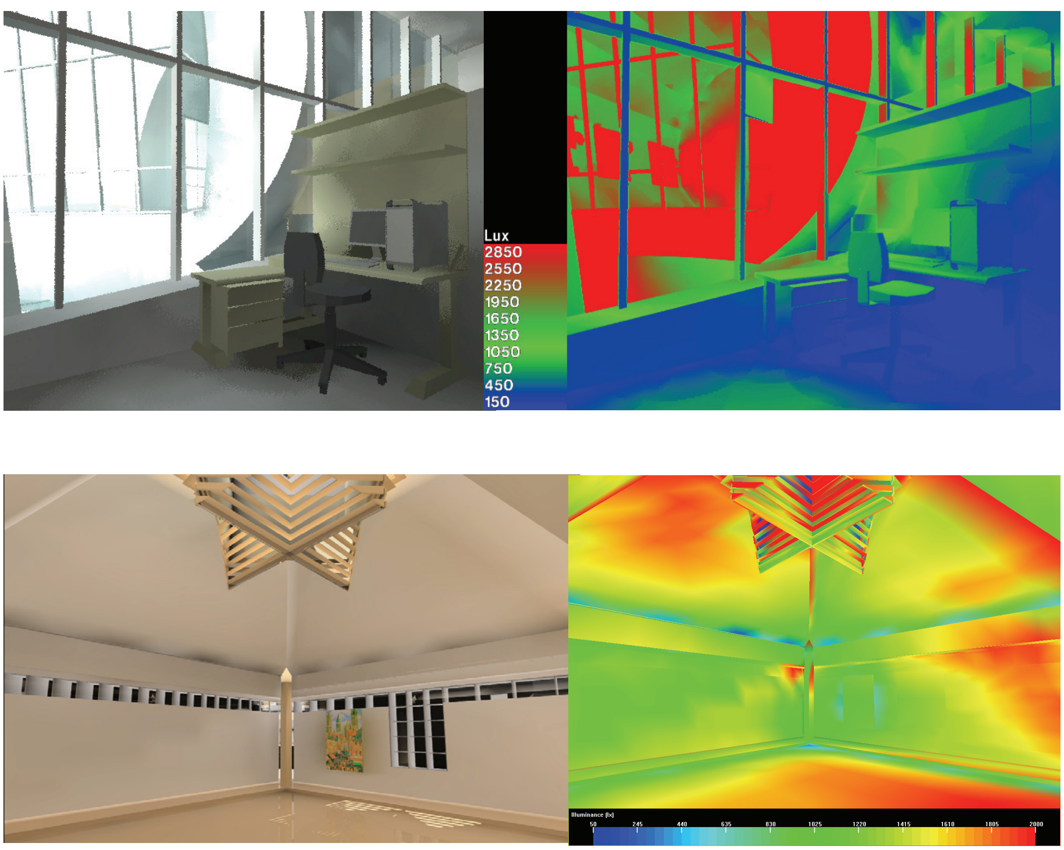


figure 2.12: Realistic renderings and illuminance false color renderings by Radiance (top, 2007) and LightScape (bottom, 2008).

Currently, many lighting simulation programs are available, and can be categorized based on their users. Users of the first category are basically designers including architects, lighting designers, and interior designers. Lighting professionals, such as engineers, lighting consultants, and lighting designers would belong to the second category. The difference between the simulation program users of these two categories is caused by the different available output and needs of users.

2.4.1 User Based Lighting Simulation Tools Comparison

Designers tend to use rendering tools [Reinhart, 2006] such as 3D Max and LightScape because the highly visual interactive features of these programs can fit the need of the visual thinking which is predominant during the design process [Broadbent, 1988]. These tools mainly focus on visualizing the architectural space with a user-friendly interface. Many of the programs, such as 3D Max, Rhino, and Maya, provide the capability of modeling complex geometries including curved shapes. The rendering function is embedded in those tools so that it creates a continual process between modeling and visualization of the design. Some other softwares like LightScape and Maxwell are independent rendering tools with powerful support for importing CAD model; thus, they can collaborate nicely with existing modeling tools including the ones mentioned above.

Geometric development and aesthetic exploration are very important activities in the architectural design process [Broadbent, 1988] [Brawne, 2003]. The ease of creating complex models in modeling (e.g., 3Ds Max, Maya) allows the designers to freely create models and explore various types of forms in a digital visual environment instead of making comparatively time-consuming physical scale models. After creating the appropriate shape of the design, the designer can use the embedded rendering functions or other separate rendering programs (e.g., LightScape, Maxwell) to run the visualization process of the space by assigning desired materials to the scene at a particular location and time. Both the modeling and rendering interfaces are designed to be friendly and simple for the designers to use. These characteristics fit the result of a web-based survey in 2003 [Reinhart, 2006] indicating designers' preference to use tools that are simple to manipulate. Beautiful, photorealistic rendering can also be very powerful when the designer is communicating with clients who may be unprofessional in architectural design and likely to be convinced by this visualization information; this could be another reason why the usage of rendering tools in the architectural process by designers is so popular.

On the other hand, **lighting professionals** are more likely to use lighting simulation tools that are capable of detailed, accurate quantitative calculations [Reinhart, 2006], such as AGi32, Lumen Design, Adeline, Ecotect, Dial-Europe, SuperLite, and others. Different tendencies between designers and lighting professionals reveal their diverse needs of data output and working styles. As we discussed above, the designer's work focuses on creating and developing different forms that fit the required functions of the building; as a result, the great amount of work focuses upon the visualization process of the space. Lighting professionals have different concerns from designers regarding daylighting. Their work focuses more on technique, such as the invention and validation of lighting systems, providing daylighting related solutions for architectural design, development of new materials for lighting, etc. These activities require them to gather enough quantitative data about lighting in order to have precise information about the lighting performance and make improvements based on the results of data analysis.

Most rendering programs provide the import function from CAD models; however, the import process does not usually go smoothly, and there are many limitations on the geometry imported [Reinhart, 2006] [Ubbelohde, 1998] [Bryan, 2002] [De Groot, 2003]. Some programs can support complex geometries. For instance, Lumen Designer, AGi32, Ecotect, and Radiance allow the user to either create complex geometry or import from other modeling tools. However, the import process is not very smooth. Compared to professional modeling software, like the 3Ds Max and Rhino, the efficiency of modeling in these tools is still not very high, and they still have limitations on complex curved shapes [the author's observation] (such as Delight, that only allows rectangular geometries [Reinhart, 2006]). Some programs, such as Dial-Europe, do not have model import and creation function at all, although it provides a list of predefined shapes for the users to choose to approximate their design.

Because of the particular needs of lighting professionals, the tools in the second category usually focus on providing support for various quantitative calculations such as illuminance and luminance distribution, daylight factor distribution (figure 2.4), etc. Some of them also have the capability of producing qualitative photorealistic renderings (e. g., AGi32, Adeline, Ecotect, Lumen Designer, and Radiance). Although many programs in this category are not very user-friendly environment, they allow the user to define the material on a more detailed level (e. g., Radiance, AGi32, Adeline) than rendering tools in the first category. Therefore, lighting professionals, who have the particular requirement of defining materials for advanced daylighting systems in order to perform accurate examinations, can benefit from these functions.

This geometry restriction and less user-friendly interface limit the creative process of the form development that has been considered as one of the essential activities in architectural design, and that partially explains why most designers refrain from them [Reinhart, 2006]. Designers usually do not have strong technical background related to lighting; therefore, they need to spend much more time learning about the meaning of quantitative data representations and how they link with the visual effect when using these programs.

All of the features of those programs discussed above reveal reasons of why designers feel more comfortable using rendering tools, while lighting professionals are more likely to use detailed and precise lighting simulation tools. In order to understand their performances of being used as lighting simulation tools during the design process, we need take a further step to look at the following aspects in those programs from a designer's standpoint: 1) whether these program are able to create successful data transmission between the program and the designer; 2) whether it can provide sufficient support for the design process to help the designer make better design decision related to daylighting.

2.4.2 Available Data Representations

In the first category, software like 3D Max, LightScape, V-Ray, FinalRender, Brazil, Maxwell, and Rhino (with flamingo as its rendering plug-in using ray-tracing and radiosity techniques) can provide highly detailed photorealistic renderings (figure 2.13). SketchUp is a modeling tool with less support for curved shapes that can also provide direct shadow rendering as its output (figure 2.14). It needs to work with Art-Lantis, a rendering tool for SketchUp, to produce realistic renderings (figure 2.3). In terms of quantitative lighting analysis, only LightScape and 3D Max can provide some quantitative analysis (figure 2.12) in the form of false color renderings that represent illuminance and luminance, most programs simply focus on simulating the visual effect (figure 2.16).

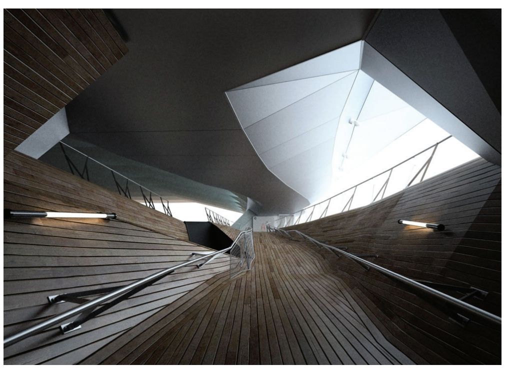


figure 2.13: Rendering by Maxwell. www.maxwellrender.com.

figure 2.14: SketchUp rendering for a housing design, 2005.

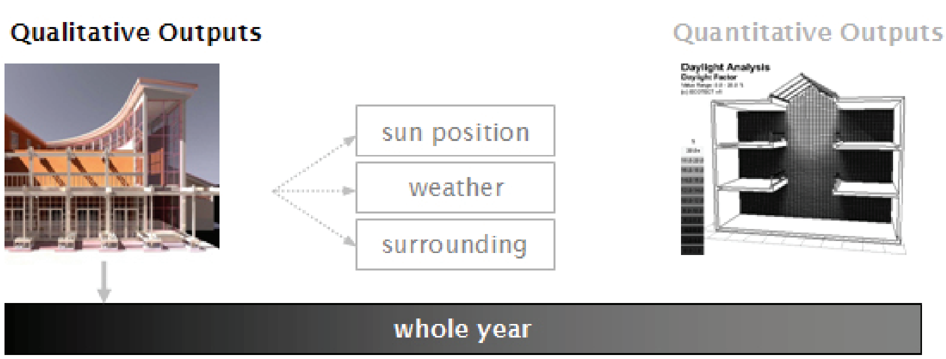


figure 2.16: Available data output and their data visualization process of tools in the first category for **designers**.

In the second category of software, sufficient quantitative analysis functions are provided. The interior illuminance /luminance distribution and daylight factor distribution for the whole scene or for specific areas are the most common quantitative data offered by these programs [Reinhart, 2006] [Ubbelohde, 1998] [Bryan, 2002]. Some programs such as DAYSIM and Adeline can also perform the daylight autonomy calculation. In addition, DAYSIM can also give a prediction of the annual electric lighting use based on the daylighting evaluation. Some programs are able to provide the user with quantitative analysis reports for each calculation (e. g., Lumen Designer, Daysim). Adeline is one of the few programs that can perform a visual comfort analysis calculated by the Radiance engine embedded.

The quantitative data is usually presented as a table, a grid with numerical values, a graphic grid, or contour lines on the plan views and section views of the building. In Lumen Designer, AGi32, and Adeline, the illuminance values are displayed in a grid within the calculated areas with numerical values or contour lines (figure 2.17). In Ecotect, a more intuitive graphic grid with different colors representing different levels of illuminance/daylight factor value is used (figure 2.4). Radiance also provides contour lines with renderings to display illuminance/luminance distribution (figure 2.18).

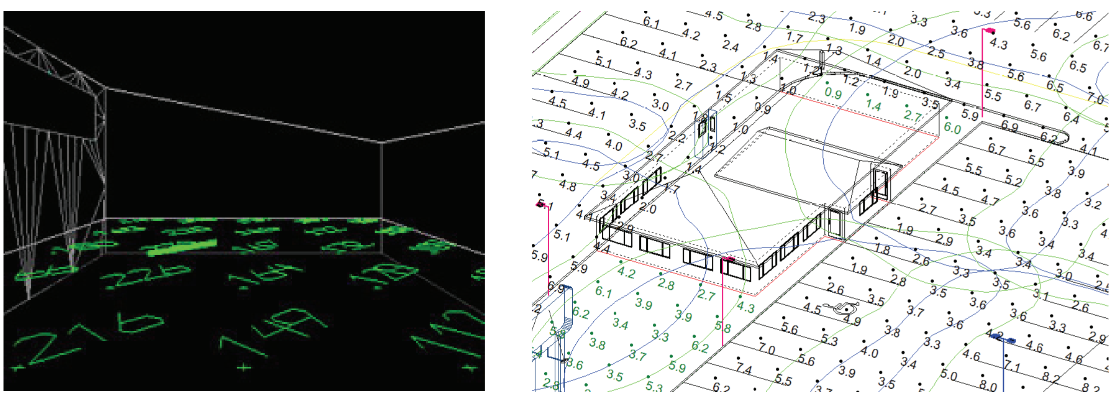


figure 2.17: Illuminance values combining with the line drawing perspective in Lumen Designer (left) and daylight factor values presented in the axonometric view in AGi32 (right).
www.lighting-technologies.com/Products/LumenDesigner/
www.agi32.com

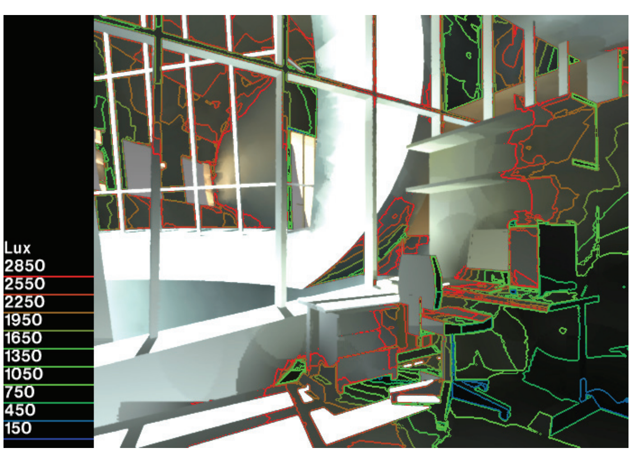


figure 2.18: Realistic rendering combining with contour lines to present illuminance distribution of the space, 2008

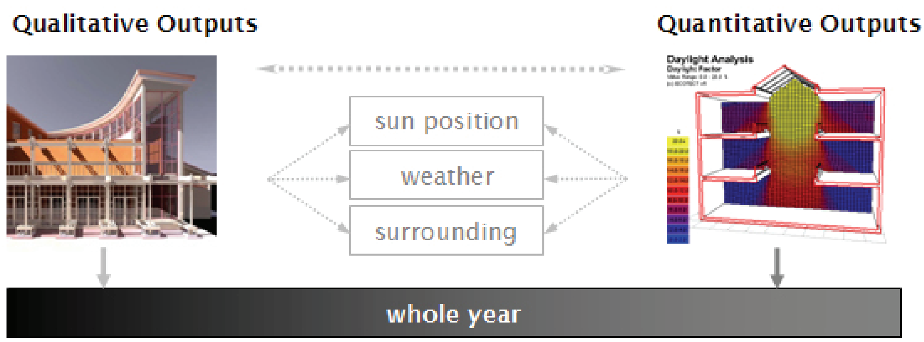


figure 2.19: Available data output and their data visualization process of tools in the second category for **lighting professionals**.

Programs like Ecotect, Lumen Designer, Adeline, AGi32, and Radiance can provide photorealistic renderings as the qualitative output. Other programs like SuperLite and Daysim do not have rendering functionality, but their output can be imported into Radiance for future rendering. Programs like Dial-Europe and DELight have no rendering function at all.

Comparing these two groups of tools, it is obvious that the programs in the second category provide much more powerful support for quantitative output than the first category (figure 2.19). Some of the programs in this category also provide photorealistic renderings, while almost every program in the first category has this function. However, there are many programs in the second category that only have quantitative output. The accuracy of the first category is higher than the second category, whereas the first category has a more user-friendly environment than the second category.

2.4.3 Data Switch

In the first category, although the accuracy of the qualitative and quantitative output (if available) from these programs is different, the way of displaying data is similar. All of them provide the visualization of the digital model with different display formats (e.g., wire frame, shaded). The user can obtain one image or an animation file after each rendering calculation. In 3D Max and LightScape, the user is able to choose either realistic rendering or quantitative illuminance/luminance false color rendering as the output. All these programs will only present one rendering output (either realistic renderings or false color images if any), and there is no way to view them simultaneously. In short, for 3D Max and LightScape, viewing different data is in a sequential way, while other tools have no data representation switch available (figure 2.16).

In the second category, for those tools that have both quantitative output and qualitative output (Ecotect, Lumen Designer, Adeline, AGi32, Radiance, etc) there are several ways to switch between displaying different types of data. Ecotect, Lumen Designer, Adeline and AGi32 are able to simultaneously present a grid with numerical values and line drawings like plan view, section view, and perspective view (figure 2.17). AGi32 has developed an application called “daylight study viewer" (figure 2.20) that can simultaneously present the renderings and false color images for multiple moments defined by the user in advance. Ecotect allows the user to preload renderings and false color images and view them easily by selecting corresponding tabs (figure 2.21), and the user can view graphic grid in a perspective view (figure 2.4).

The switch between quantitative data and the qualitative data are quick (if we consider line drawings as simple qualitative data). However, the line drawing format with almost no material and lighting effect, so it is insufficient to inform the designer the realistic visual effect of his design. In order to perform the data switch between quantitative data and qualitative photorealistic renderings, only AGi32 and Ecotect have provide some assistance, and the process in other programs is more or less the same as in programs in the first category. The user can only view either quantitative data or quantitative data each time in most programs (figure 2.19), unless the user decides to put the rendering windows next to the quantitative analysis result himself, and it is sometimes impossible in many programs.

Therefore, in terms of the data switch between quantitative data and qualitative photorealistic renderings, the user has to view different data in sequence in both two categories.

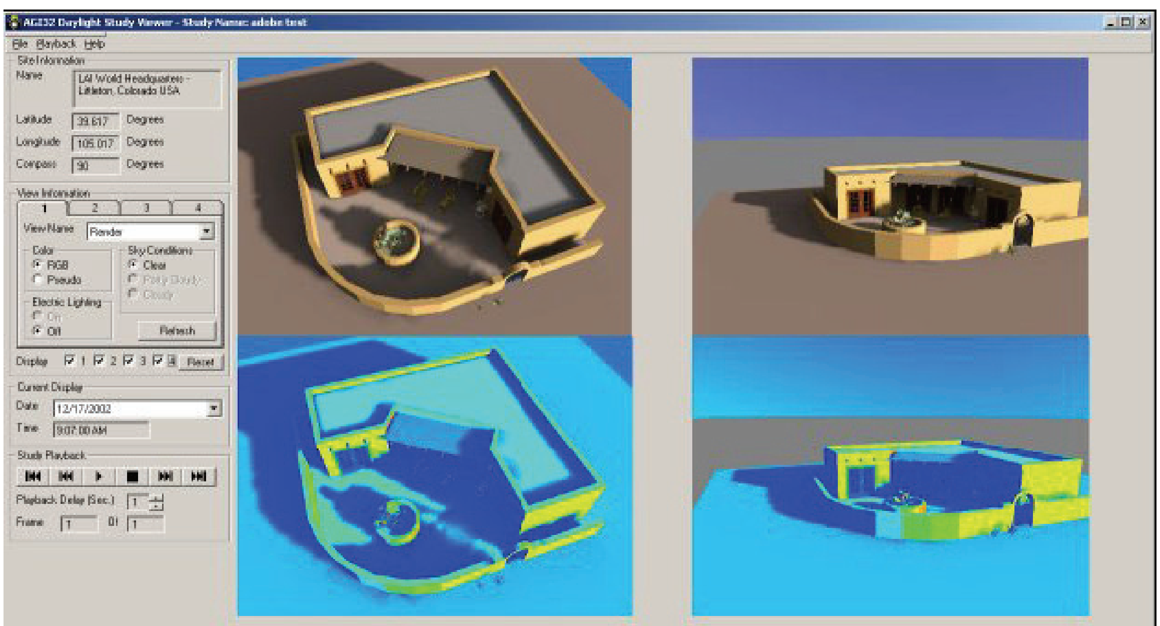
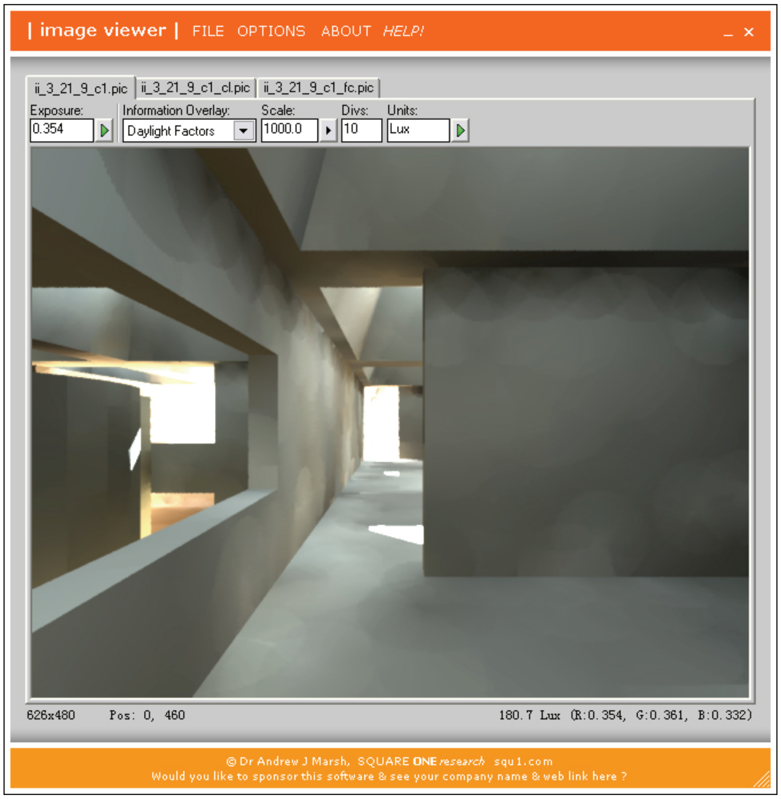


figure 2.20: "Daylight study viewer" in AGi32 which can present renderings and false color images simultaneously.



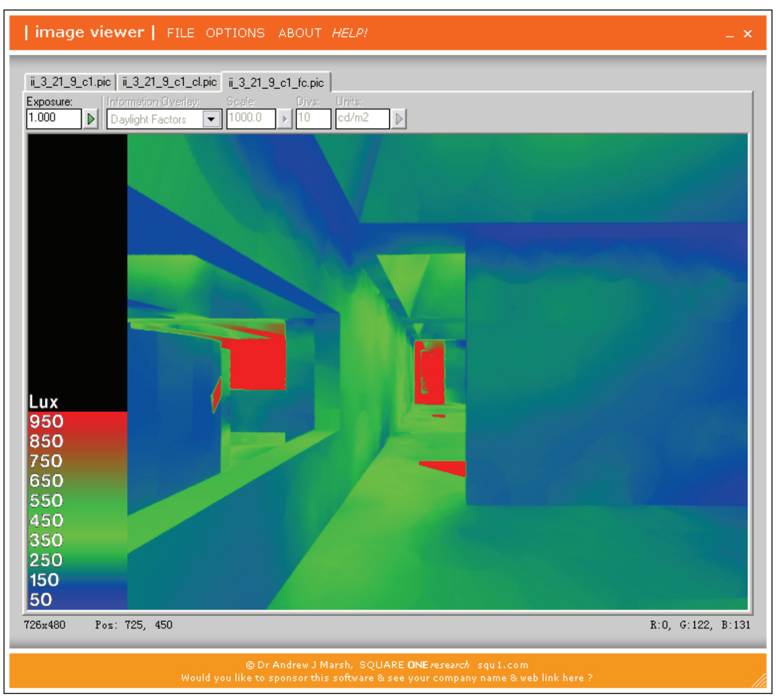


figure 2.21: "Radiance image viewer" in Ecotect which presents the rendering output and can allow user to manually load different types of renderings and present them in tab.

2.4.4 Daylighting Performance and Outside Environment in Data Output

There are three factors of the outside environment that can affect inside daylighting performance. These are: sun position, sky conditions (weather), and physical surroundings. Programs like 3D Max, LightScape, Maxwell, V-Ray, FinalRender, and SketchUp in the first category have the ability to select different sun positions by defining the time and location (by cities in the program's database, or by latitude and longitude). Except for SketchUp, these tools also allow the user to select different sky conditions, but the input parameters are rather simple. The surrounding environment totally depends on how much the user models it and assigns materials and in what level of detail. It is obvious the support of environmental settings in these programs is weak.

Although they have simple outside environment parameters as optical input for qualitative rendering output, there is no related environmental information displayed in the final data output with the renderings (figure 2.22). Generally, the way for the designer to check with these outside parameters linking to the rendering's daylighting performance needs to seek them in several definition panels or display all of these panels at the top of the program (this is a very inconvenient and cumbersome procedure, and is sometimes impossible) [based on the author's experience]. In short, in most of the data output, the link between the daylighting performance and the outside environment (sun position, sky condition, and physical surroundings) is in a very non-intuitive way or completely absent.

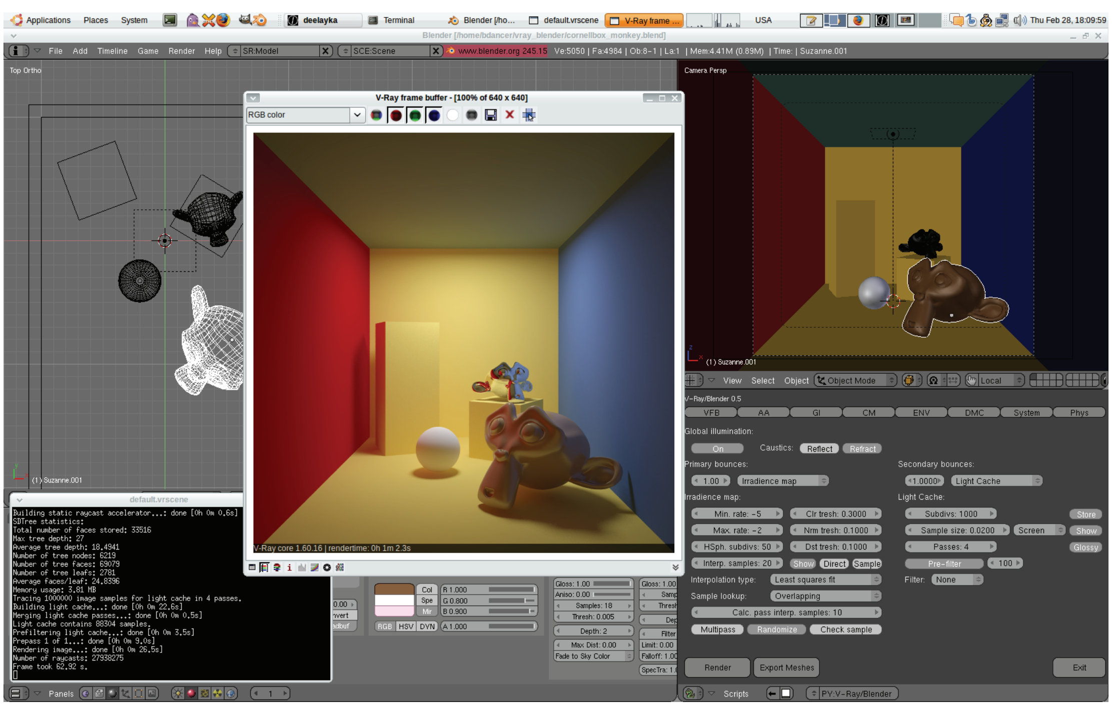


figure 2.22: Maxwell presents only one rendering output each time with no other information related to the outside lighting condition, so as many other tools in the first category for designers.

The built-in sky models defined in the second category are much more complete and follow the CIE standard. Most of the programs provide CIE clear sky (with or without sun), CIE standard overcast sky, and uniformly overcast sky (figure 2.23) (e. g., Ecotect, Lumen Designer, Adeline, Radiance, SuperLite, Dial-Europe) [Ubbelohde, 1998] [De Groot, 2003] [based on the author's experience]. Most programs are able to let the user specify the sun position by defining the time and location information from either the latitude and longitude or the built-in map system. Some programs allow the user to define the condition of the physical surrounding. However, in terms of linking these environmental information with quantitative and qualitative data output, the situation in this category are more or less the same as in the first category (figure 2.21, 2.19). The user has to go back to the related setting interface to look at those parameters.

In summary, the support of setting the outside environment in the calculation is better in the second category, but both types of programs lack the link between performance and the outside conditions in their data output. This important link becomes even weaker in the designer's mind when he is trying to make decisions that need to take this connection into account.

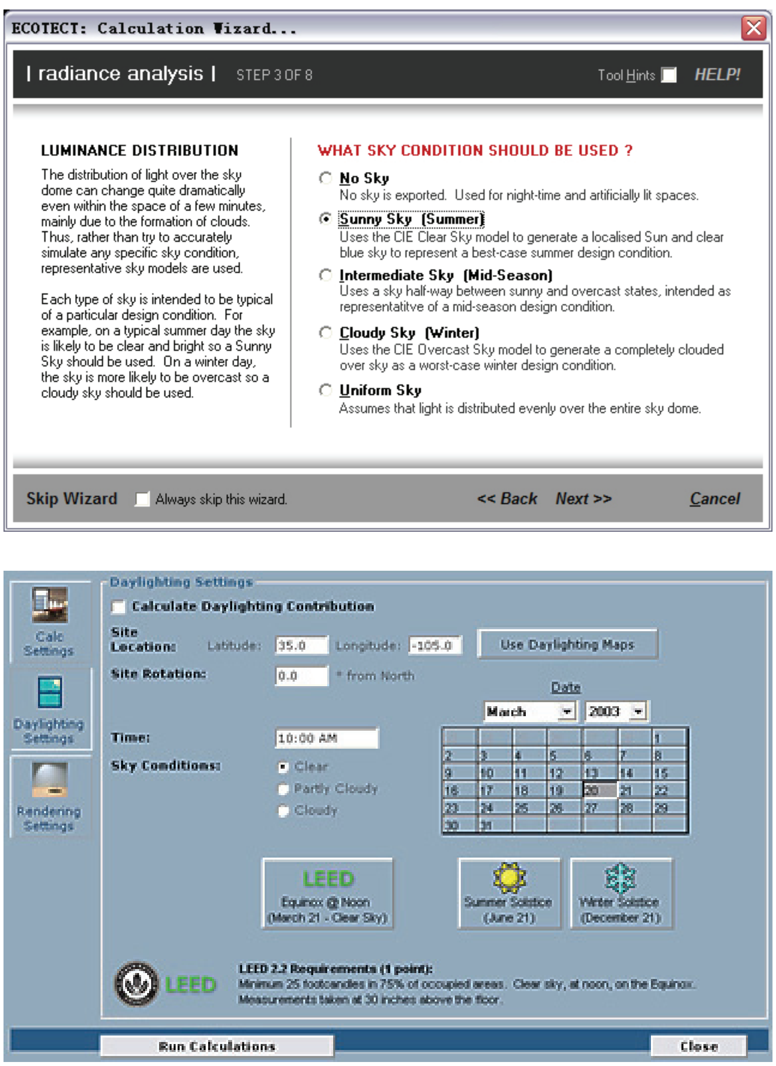


figure 2.23: The sky setting panel in Ecotect (top) and Lumen Designer (bottom).

2.4.5 Data Output and Time Variation

All of the programs discussed in the first category have the same feature regarding their data output for daylighting performance and the period of time represented. The rendering output always represents individual in each calculation. They are capable of generating animations as one type of output that can cover a period of time; however, it is still composed of a series of calculations for each frame and is a time-consuming process. If the user wants to have an annual estimation of his design, he has to manually select several crucial moments to run simulations depending on his own lighting design experience, rule of thumb or available guidelines. The link between daylighting evaluation and the period of time is simply one rendering corresponding to one single moment (figure 2.16). The user would easily neglect some crucial moments and rely on performance presented in several individual moments to make the evaluation. It clearly cannot provide enough support for helping the designer make better design decisions that consider daylighting performance over the whole year.

Some programs in the second category do provide some annual quantitative analysis. For example, Many programs like Ecotect and Adeline produces daylight factor distribution graph (figure 2.4), and DAYSIM provides daylighting autonomy calculation. But the daylight factor cannot truly be considered as an annual evaluation since it only takes into account overcast sky. The daylight autonomy can simply tell the user in what percentage his design receives enough light over the year, but it cannot really tell the user when the design receives enough light and when it does not.

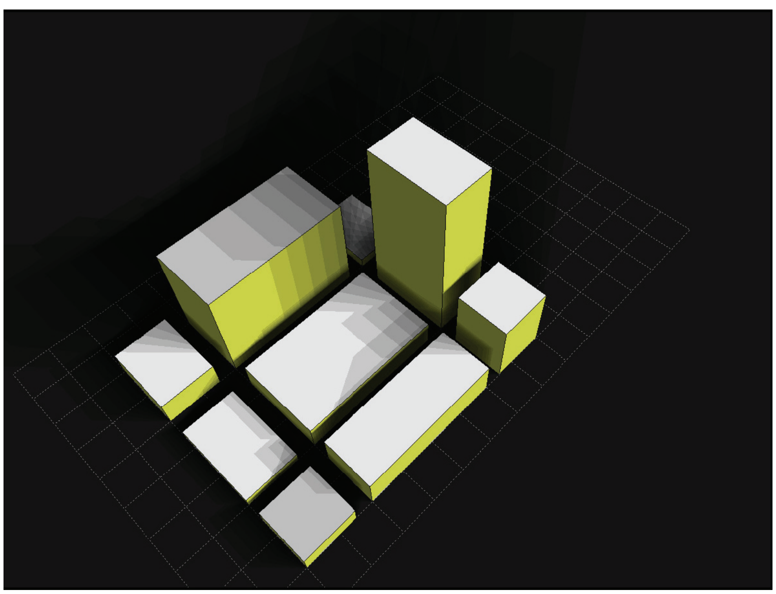


figure 2.24: Annual shadow analysis in Ecotect, image credit: Eleftheria Fasoulaki, SMArchS, Computation and Design

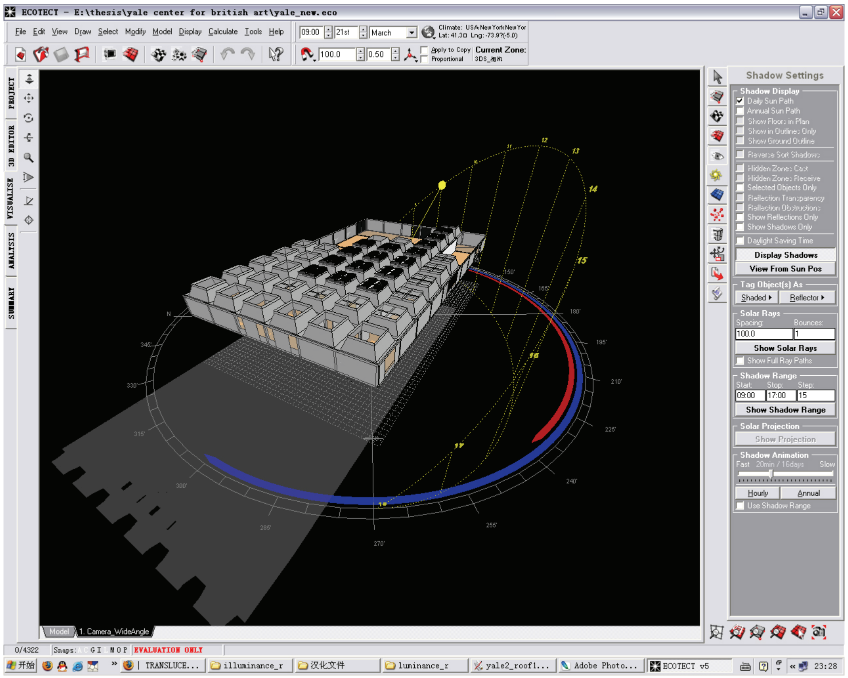


figure 2.25: 3D sun chart in Ecotect

The "daylight study viewer" in AGi32 can present renderings and false color images for multiple moments (figure 2.20). Ecotect creates a new way of checking direct shadows for the entire year by presenting annual shadow ranges in the line drawing renderings (figure 2.24). Also, the user may actively change the time – either time of day or time of year, keeping the other fixed – and view on-the-fly in Ecotect's 3D sun chart (figure 2.25). These features in Ecotect can be considered as a quick link between the simplified qualitative outputs (line drawing rendering) and the time variation. Nevertheless, the line drawing is not powerful enough to inform the user the visual effect of the space. In terms of the qualitative photorealistic renderings and time variation in the data output display, except for AGi32's "daylight study viewer" other programs still do not support this link. In programs that provides photorealistic rendering function (e. g., Adeline, AGi32, Ecotect, Lumen Designer, Radiance), the user is only able to have one rendering output each time and manually collect them for further analysis.

In these two categories, programs do not really provide powerful method to link their quantitative and qualitative output with the time variation, except for AGi32's "daylight study viewer" (figure 2.16, 2.19). The user has to manually collect data for every individual moment and organize them together to perform annual performance analysis.

2.4.6 Data Output and Design Goals

The rendering tools in the first category provide rendered pictures of single moments as their primary output. The qualitative rendering output simply provides the prediction of the space's visual effect; thus, there is no information embedded that can directly indicate if the visual effect reaches the designer's initial goals. Creating the link between the qualitative data and designer's design goals has to be done by himself in his mind based upon experience or available guidelines. In other words, the link between data and initial design goals does not exist in programs in this group. However, providing such a link in the lighting simulation tool between the data output and the design goals is greatly helpful for the designer to accelerate the speed of analyzing the data and to avoid possible misunderstanding of the data that might affect future decision making as an embedded professional lighting assistant.

In the second category, quantitative output and qualitative renderings are the major output. Compared to the first category, some programs allow the designer to identify the function of the space (e.g., DAYSIM, Dial-Europe) and perform analysis based on the predetermined function. Although different spaces have their own particular functions, function can not be directly considered as a design goal in that it simply refers to the people's general activities in this space, and it does not concern of the difference between projects and aesthetic considerations. Many other programs simply not have this function at all, and the user needs to analysis the data himself to determine whether the space's performance reaches his design goals. Therefore, the user himself is still responsible for evaluating the data output from these programs to see if the lighting performance reaches his initial design goals in terms of quantitative aspect and qualitative aspect. The link between the output and the design goal is missing in the data display.

2.4.7 Comparison Summary

From the comparison of the existing lighting simulation programs, similar features of the data transfer between the program and the user can be found in the first category referring to designers and the second category referring to lighting professionals. Most rendering tools in the first category have the qualitative photorealistic rendering as the primary data output format. The way they present renderings is one image each time. Definition of the parameters related to the outside lighting environment such as the sun position and the sky condition is allowed in most of the programs, but related information is not included in their output display. On the other hand, the simulation tools used more frequently by lighting professionals have sufficient quantitative output and qualitative photorealistic rendering output with high accuracy. There are some combinations of these two types of data representations in their data display; however, the overall data transmission between programs and users occurs in a sequential way and does not allow the user to quickly switch between different types of data. Environment settings are better supported with high accuracy in the second category; but the output display still does not emphasize the link between the performance and the relevant outside lighting environment as in the first category. Neither group has an efficient data visualization process that can truly efficiently inform and support the daylighting design (figure 2.11, 2.16, 2.19).

Chapter 3

Thesis Research Method

3.1 Objectives of Thesis

The inefficient data visualization process between programs and designers in existing daylighting simulation programs discussed in the previous chapter greatly interrupts the design process and does not truly support the designer to understand daylighting performance comprehensively and make appropriate design improvement, which can meet the lighting requirement and adapt to the local weather condition and surroundings over the year at the same time.

Therefore, the thesis decides to create a more efficient data visualization method[2] that addresses all these issues simultaneously. It aims to simultaneously present quantitative graphs with qualitative realistic renderings and provide the user easy access to data over the whole year; meanwhile it closely links the daylighting performance displayed in these quantitative and qualitative data with corresponding outside environmental information, such as the sun position, sky condition, and physical surroundings. It is able to assist the designer to comprehensively interpret and evaluate these various types of data while minimizing his effort of collecting and searching data so that the design can concentrate on his design activities in a smooth way.

3.2 Thesis Approach

This data visualization method uses the existing research work developed by a PhD student, Sian A Kleindienst at the Building Technology Program at MIT Department of Architecture, as one data output. This temporal map[3] (figure 3.1) [Kleindienst, 2008] is a new form of data that shows daylighting performance of the AOI (the area of interest, it is an area which the user is interested in getting detailed quantitative information) over the whole year and takes into account weather variation. Instead of simply indicating how much light the space gets, it is a goal based metric and presents how closely these design goals are met over the whole year. Four types of goal-based dynamic metrics are currently under developing to analyze the space's performance from the four critical aspects; these are whether the space gets enough light (illuminance based), whether the space has glare issues (luminance based), whether the space gets too much solar heat gain, and whether the light distribution is satisfying [Andersen, 2008]. All these attributes meets the need of the data visualization during the design process in terms of daylighting,

[2] This data visualization method is part of the broader LightSolve project which is currently under developing at MIT Daylighting Lab and collaborating with RPI Department of Computer Science.

[3] More detailed information about the temporal map is introduced in the following paper:
Sian Kleindienst, Magali Bodart, Marilyne Andersen. 'Graphical Representation of Climate-Based Daylight Performance to Support Architectural Design'. Submitted to Leukos, 2008

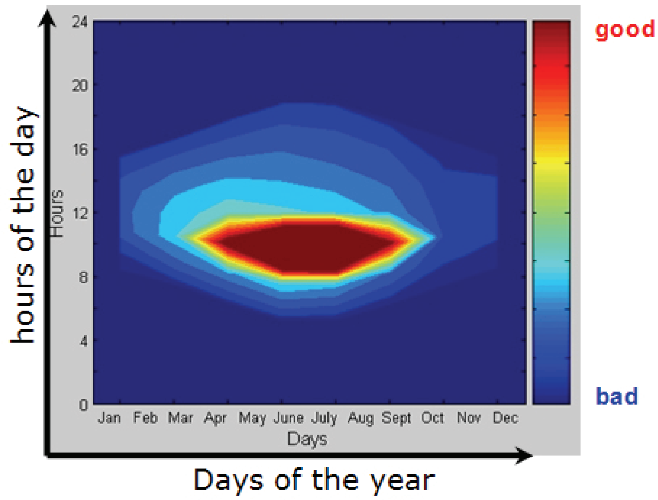


figure 3.1: The temporal map-the x-axis represents days of the year, the y-axis represents hours of the day. The red color represents the tested area reaches the designer's initial design goal set in advance; the blue color represents the space fails to achieve the goal.

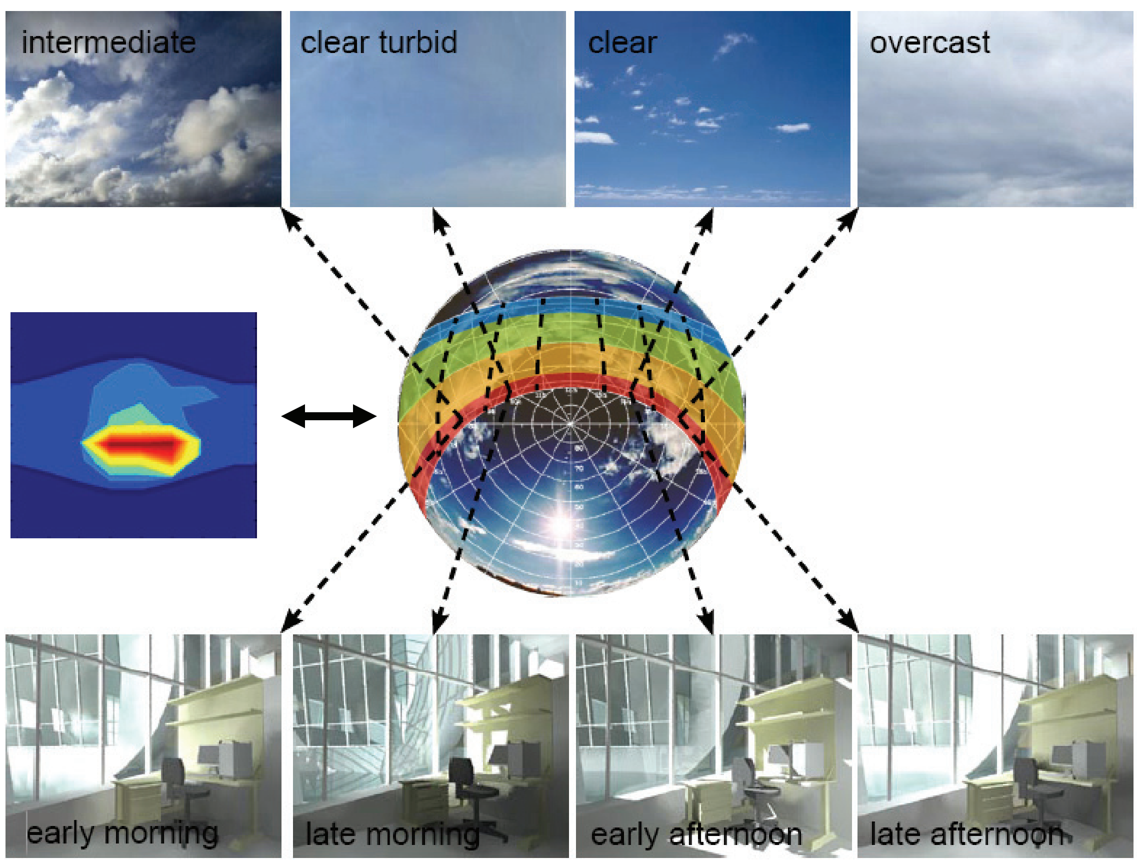


figure 3.2: In the calculation of the temporal map, it splits daylight hours into 56 moments which have similar sun position and weather conditions. Each moment can be linked to particular point on the temporal map, qualitative renderings, and corresponding outside lighting conditions.

therefore, the author decides to choose this metric as the major quantitative data output in the proposed data visualization method.

Since an original method [Kleindienst, 2008] is developed to generate temporal maps by categorizing the weather into four sky types as clear, clear turbid (polluted), intermediate, and overcast (ASRC-CIE sky model by Perez) and splitting the daylight hours over the year into 7 x 8 periods that have similar sun position and weather conditions (figure 3.2). The author intends to integrate realistic renderings for these 56 moments with the temporal map (figure 3.2), hence, the author decides to use the render engine [Cutler, 2008] currently being developed by RPI Department of Computer Science as a way of quickly producing accurate renderings for the proposed method (the engine is yet not ready to use, so all the renderings in this thesis were produced in 3Ds Max and Radiance).

The purpose of the proposed data visualization method is to simultaneously present quantitative and qualitative data and dynamically link photorealistic renderings for the 7 x 8 periods with the temporal map over the whole year. In addition, it intends to integrate the environmental information such as the sun angles, sky conditions, and building's physical surroundings corresponding to these 56 moments. As a result, the designer is able to understand the daylighting performance more comprehensively, and find out advantages of his design and potential weakness while aware of the influence of the outside circumstances in the performance; therefore, the platform will be able to increase the chance for the designer to take the advantage of the natural environment and appropriately adapt his design to the particular location.

Chapter 4

Design and Development of an Interactive Data Visualization Platform

4.1 Concept of Proposed Platform

This data visualization platform aims to link the annual climate-based temporal map dynamically with the renderings for all AOIs, related sky dome views, and local surroundings. The designer is able to browse through the temporal map, and all the renderings and outside environmental information are updated simultaneously (figure 4.1). In addition, it is able to present analysis results for several areas that the designer is interested in, instead of simply displaying results for one single area per time. Furthermore, it allows the designer to view the daylighting performance from a climate-based aspect or any weather condition (clear, clear-turbid, intermediate, and overcast) that he is interested in. Thus, the designer can check the quantitative and qualitative data simultaneously and easily access the performance for any AOI at any moment over the year while knowing corresponding outside environmental variations.

The data visualization platform was developed using the Java 6 platform. The size of the platform is 1020 pixel x 750 pixel, which is designed for most screen sizes (1024 pixel x 768 pixel) currently used. The platform contains two basic components: the data exploration panel on the right and the control panel on the left (figure 4.2).

The data exploration panel uses the Java desktop pane so that it can present analysis results for several different design projects in internal windows (figure 4.3). The default layout (figure 4.2) of the data exploration internal window allows the user to view analysis results for at most 3 different areas that he is interested in. It contains quantitative temporal maps, the rendering for the sky dome and physical surroundings, the elevation/plan view with sun ray, and the actual digital model.

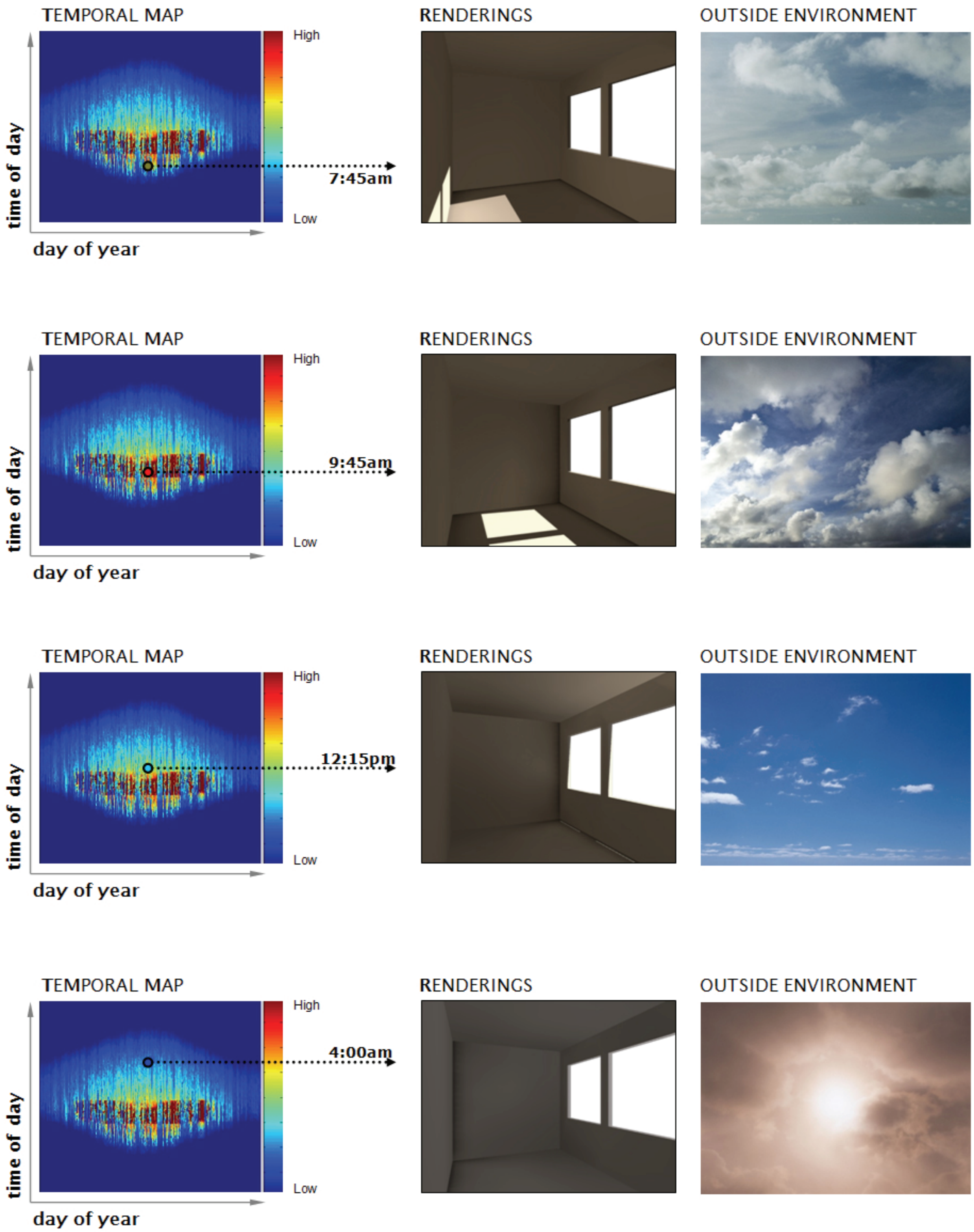


figure 4.1: In the proposed data visualization method, when the user is browsing the temporal map, the rendering and corresponding outside lighting condition will be updated simultaneously.

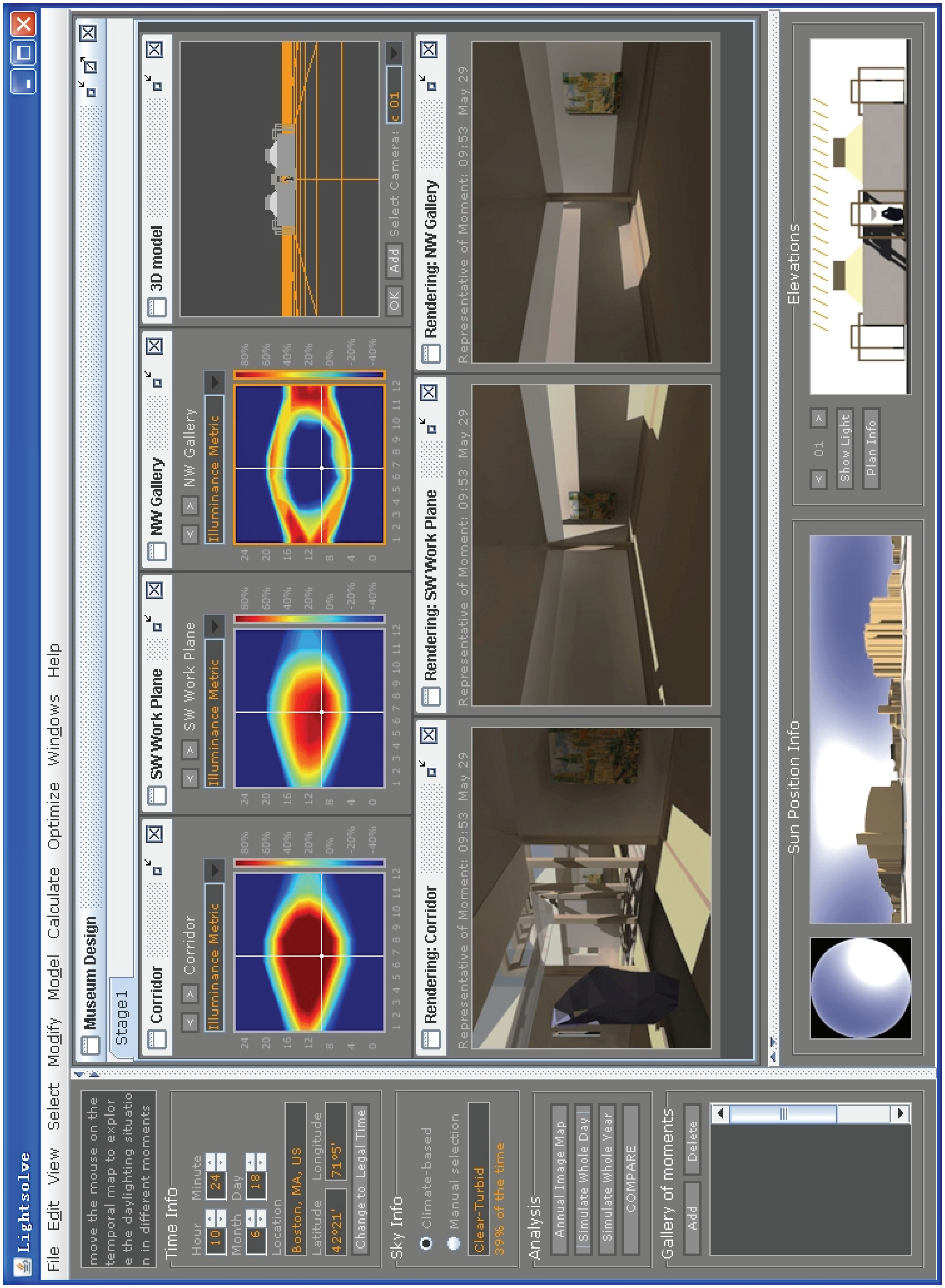


figure 4.2: The complete view of the data visualization platform.

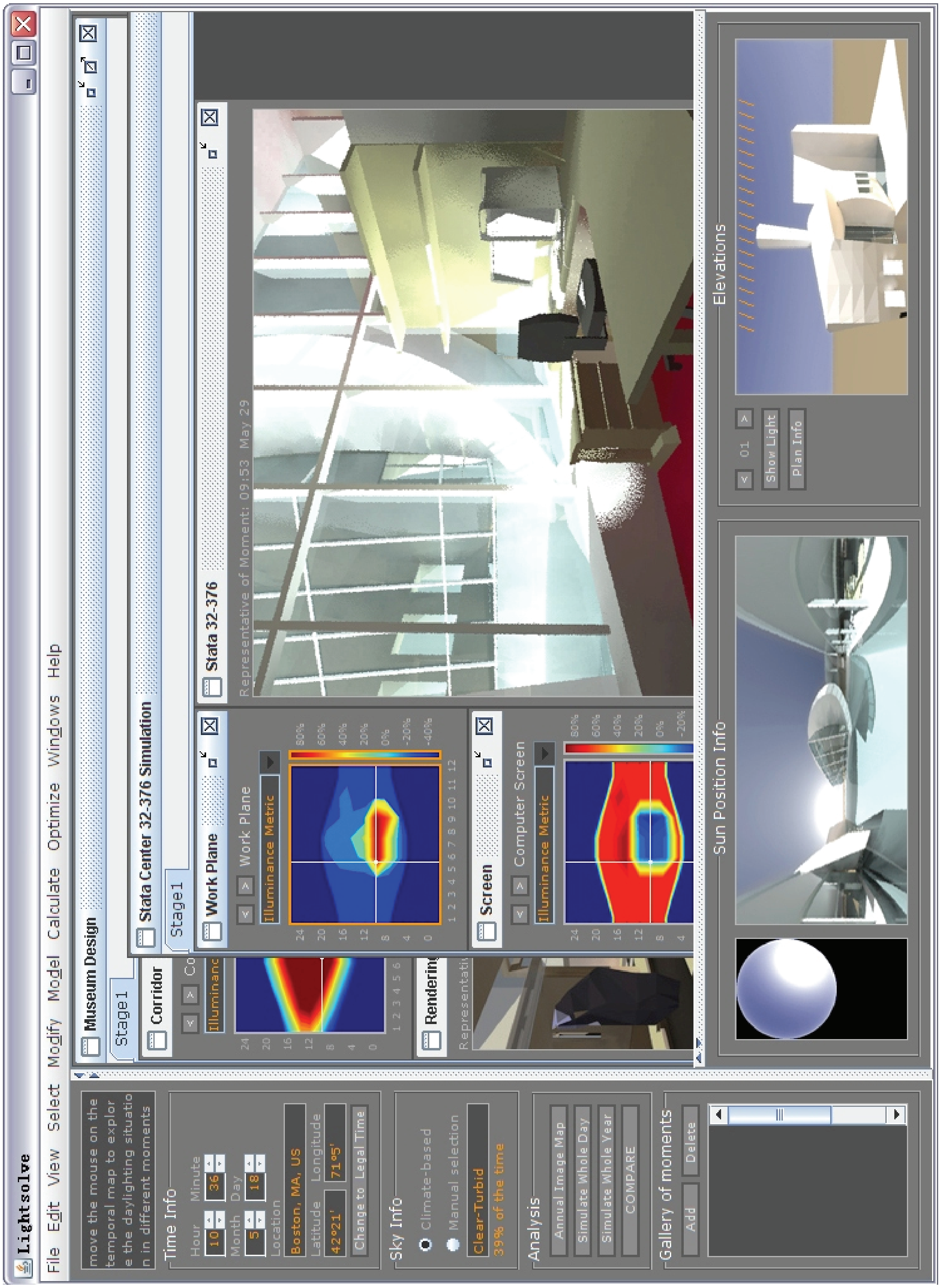


figure 4.3: The platform can allow the user load different design projects simultaneously.

4.2 Interactive Data Browsing

When the designer is browsing the temporal map, the corresponding rendering window automatically updates its rendering with time and date information for the representative moments with corresponding to the current cursor position (figure 4.4). In the default layout where three temporal maps are presented at the same time, the cursor browsing on any temporal map will drive the other two cursors to move in the same manner, and the other two AOI renderings will update as well. By default, the AOI rendering is produced under the dominant sky condition for that representative moment. The cursor movement on the temporal map also triggers all the corresponding outside environmental information (sky dome, surrounding, and sun rays) and the elevation renderings (figure 4.4).

At the same time, the “time info” panel and “sky info” panel (figure 4.5) on the left control panel automatically respond to this interactive browsing of the year on the temporal map. The “time info” panel always presents the solar time for the current cursor position on the temporal map. The user can switch to the legal time by pressing “change to legal time” button. When the default “climate-based” option is turned on, the sky info panel will show the dominant sky condition and its occurrence (in percent of time) that associates to the current period. The user can also turn on the “manual selection” option and define the sky condition from the combo box (figure 4.5) that he prefers to look at. In this case, the sky info panel will always present the occurrence percentage of the chosen sky type, and AOI renderings will be updated as renderings corresponding to this change.

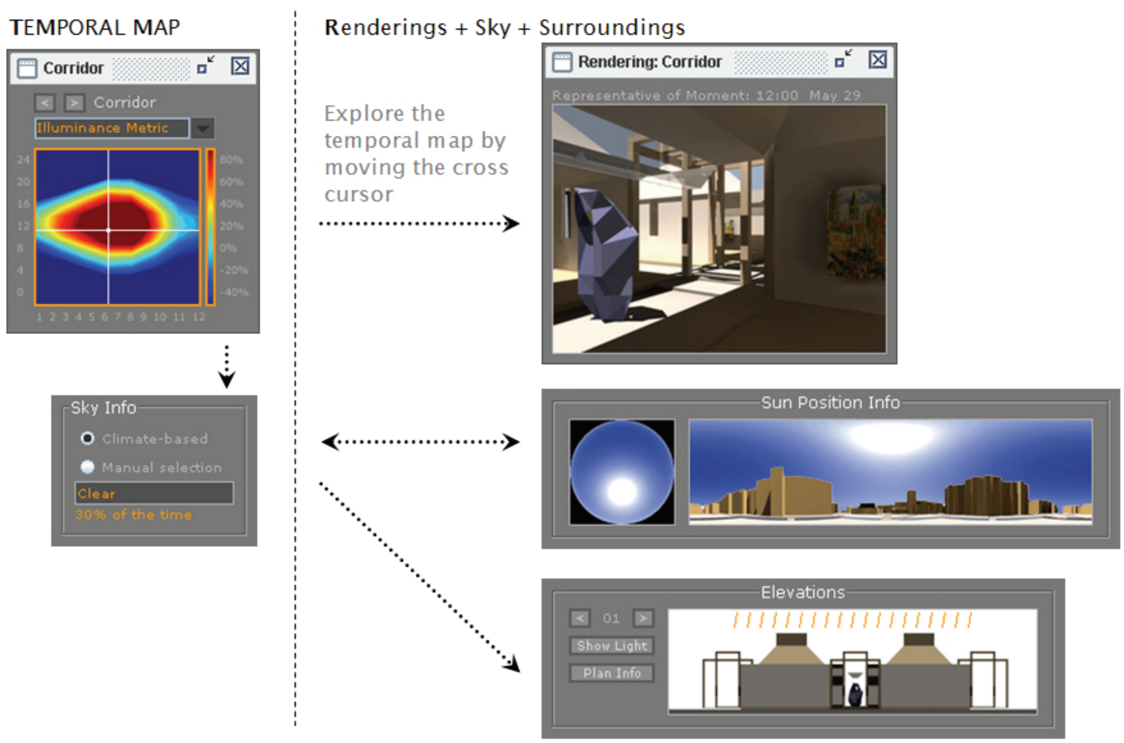


figure 4.4: Dynamic link between daylighting performance and outside lighting environment.

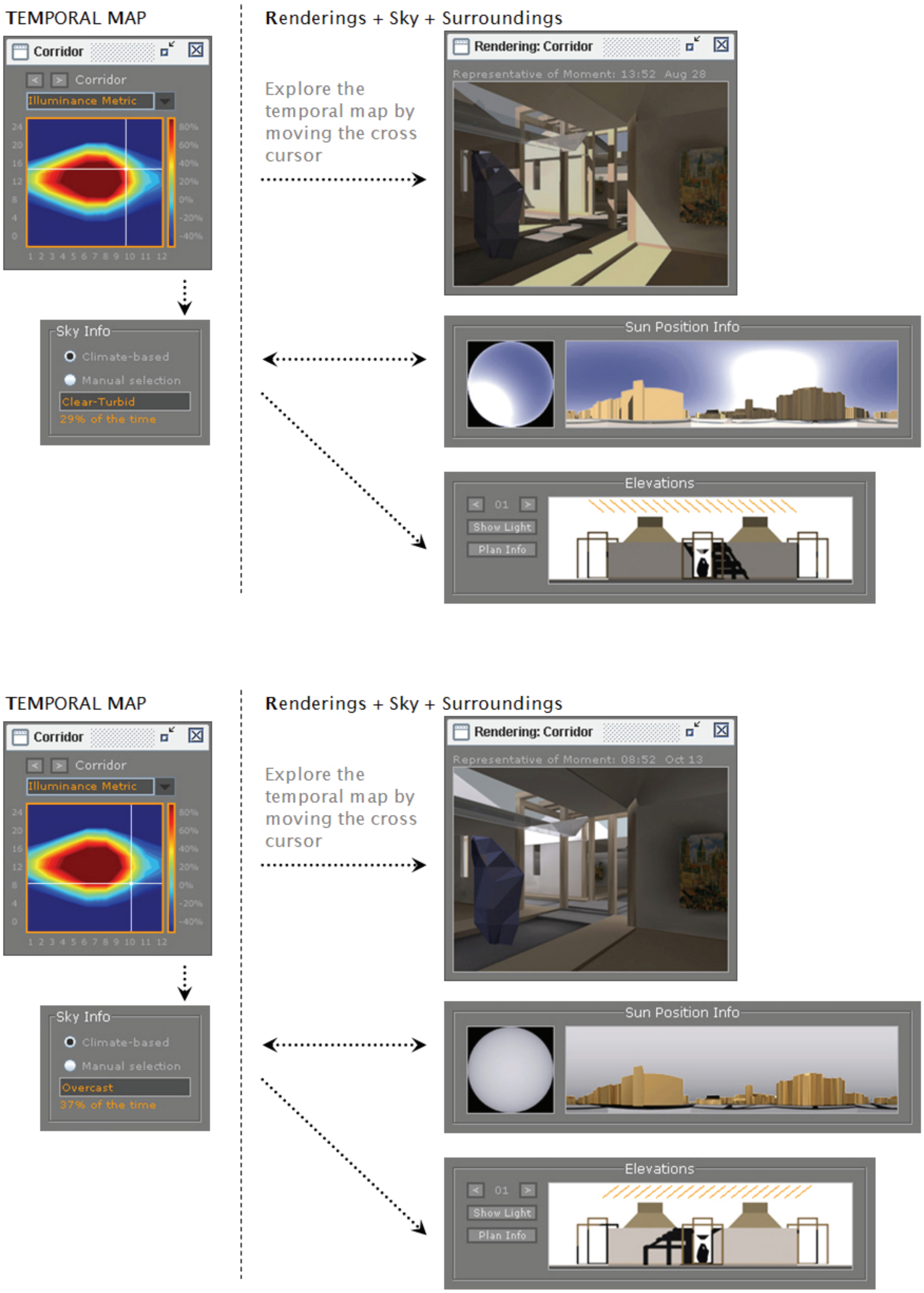


figure 4.4: Dynamic link between daylighting performance and outside lighting environment.

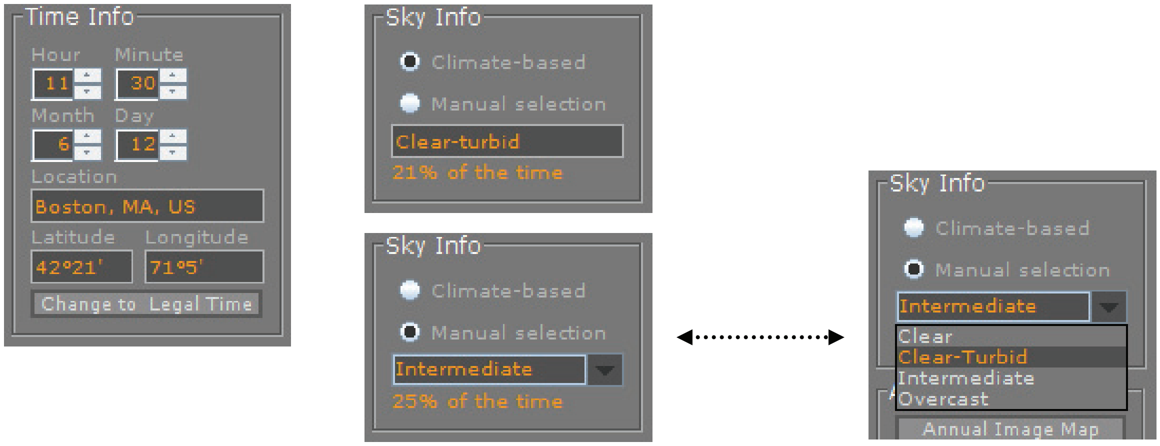


figure 4.5: "Time Info" panel and "Sky Info" panel.

By dynamically linking the quantitative goal-based temporal map with photorealistic rendering for corresponding AOI, the designer can better understand how daylighting performance varies over time from both aesthetic and technical perspectives and whether the space reaches his initial design goal. More importantly, the interactive browsing integrates the local weather variation and outside conditions into the daylighting evaluation in an intuitive way. Thus, the designer is aware of the potential impact of the outside environment on the space's daylighting performance and can seek possible design solutions that fit the initial goal and the local environment.

4.3 Additional Simulation Methods

The data visualization platform's interactive browsing of the temporal map creates a quick switch from quantitative data to qualitative data, and lets the user easily access the daylighting performance over the whole year based on the actual climate variation instead of a set of static moments under fixed weather condition. In addition, several functions have been embedded in this platform in order to enhance the link between quantitative and qualitative data - i.e. between the performance and the influence of the outside environment. The overall effect is to provide a better informed design process.

4.3.1 Annual Image Map

In order to help the user understand better the innovative goal-based temporal map, a qualitative translation (figure 4.7) called the Annual Image Map has been developed. The platform displays a diagram (figure 4.6) that is composed of 7 x 8 renderings corresponding to the 7 x 8 periods of similar moments in the temporal map, by pressing the "Annual Image Map" button on the Analysis panel (figure 4.8),. By default, each rendering will show the dominant sky type for the period it represents. The annual image map can be considered as a "visual temporal

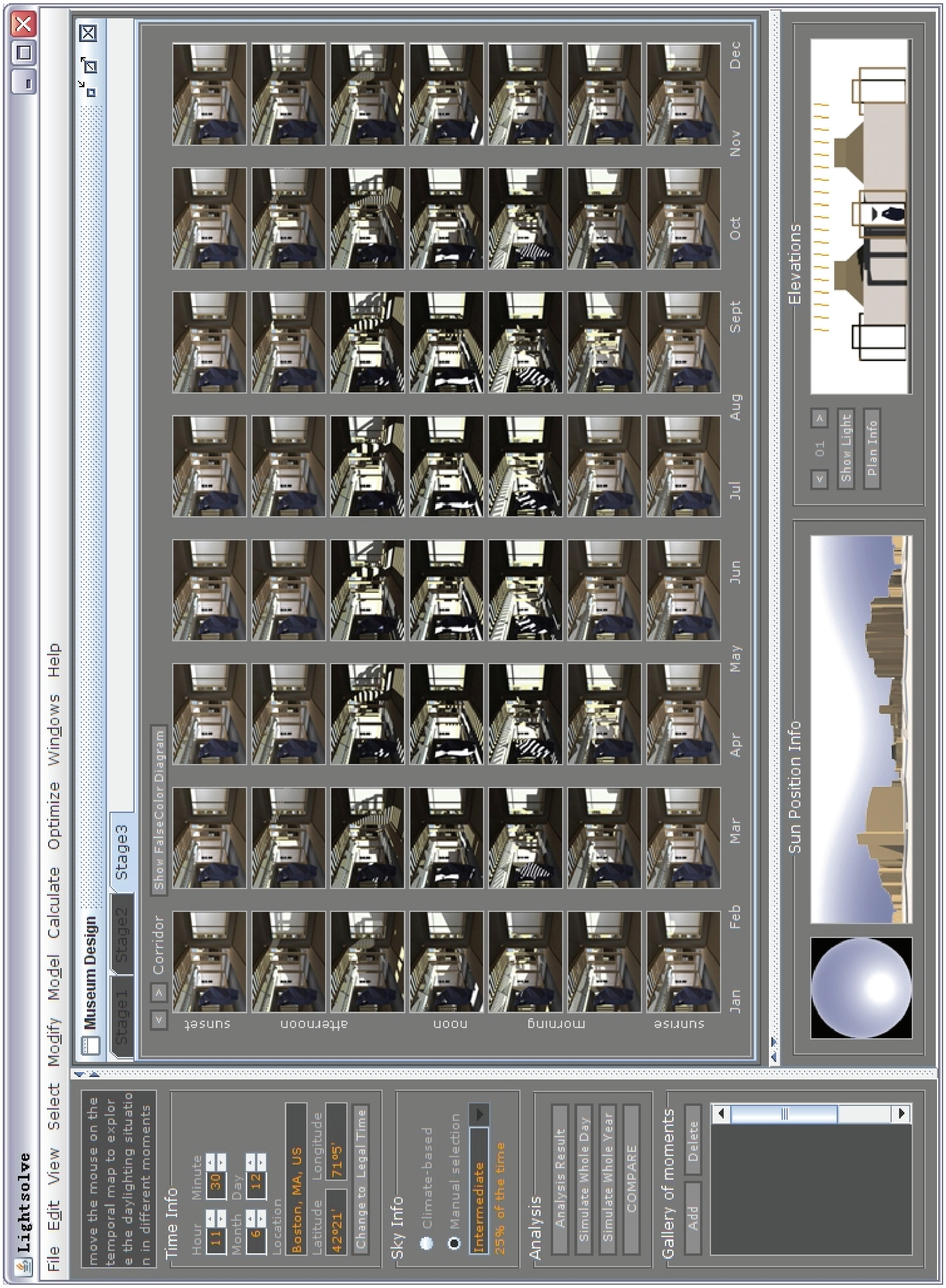


figure 4.6: Annual Image Map working as a “visual version temporal map”.

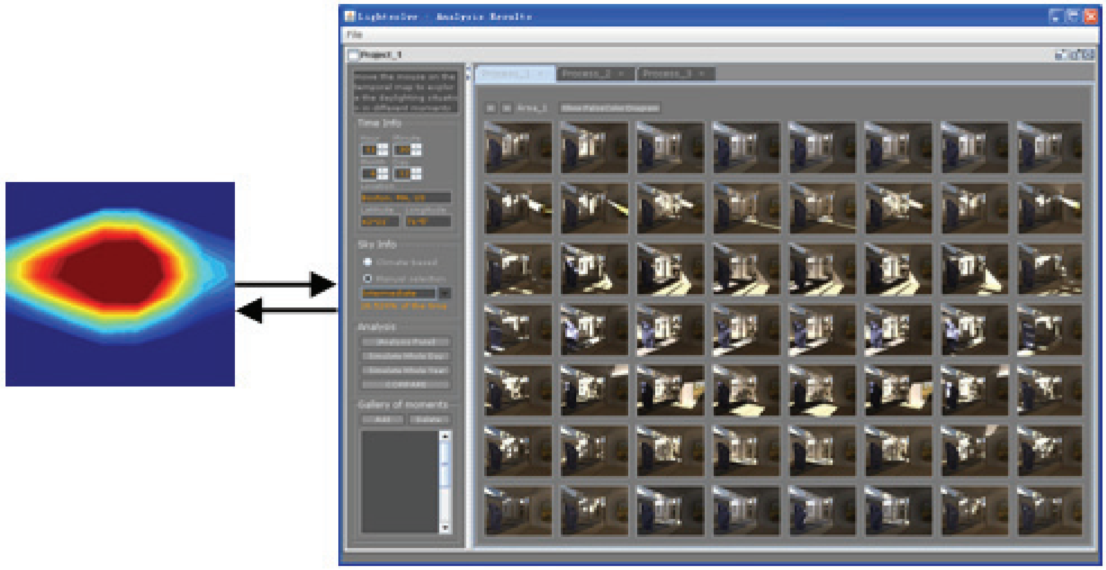


figure 4.7: Translation between the quantitative temporal map and qualitative annual image map.

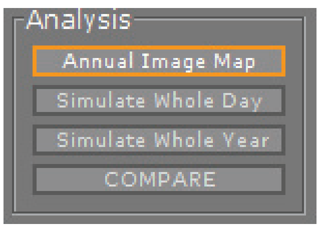


figure 4.8: Analysis control panel.

and represent the performance variation over time in terms of visual effects. Annual False Color Diagrams for illuminance and luminance will also be available so as to translate the goal-based performance information in the temporal map or the visual information in the annual image map to variations of light levels over the year. The user can also easily access other annual image diagrams or annual false color diagrams by pressing the forward and back buttons on the platform (figure 4.6).

4.3.2 Simulation over Time and Date

The features “Simulate Whole Day” and “Simulate Whole Year” in the analysis panel (figure 4.8) are able to produce an “animation” of a day passing or of a given same time over the whole year (figure 4.9). Renderings will be displayed in a time sequence and overlapped using “fade-in” and “fade-out” effects in between. The cursor on the temporal maps will move vertically over time at a given date or horizontally over dates at a given time. The environmental data (sky dome view, surroundings, and elevation with sun ray) will be animated in the same way (i.e., as a response to temporal map browsing or time/date simulations).

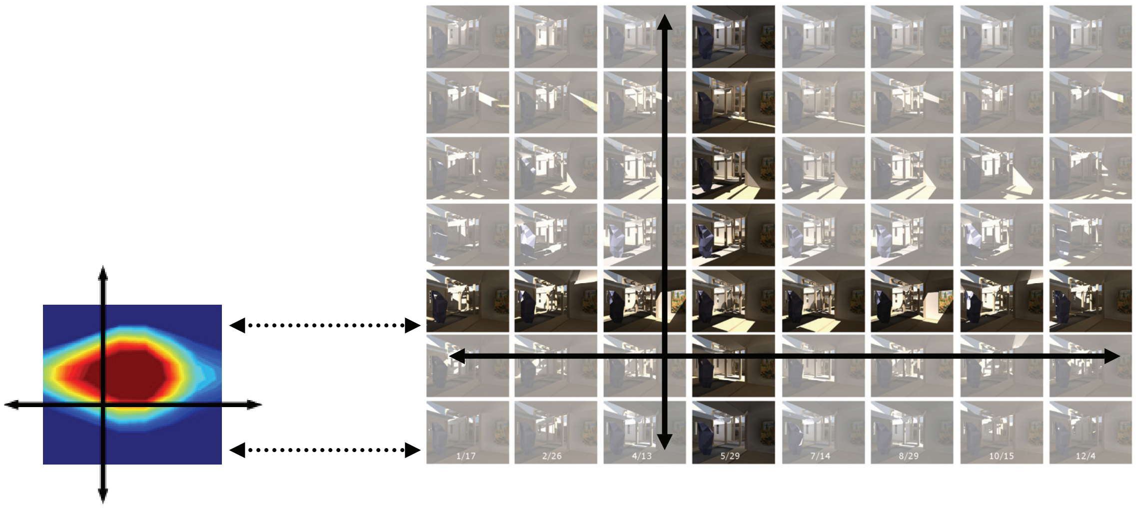


figure 4.9: Translation between the quantitative temporal map to qualitative realistic renderings.

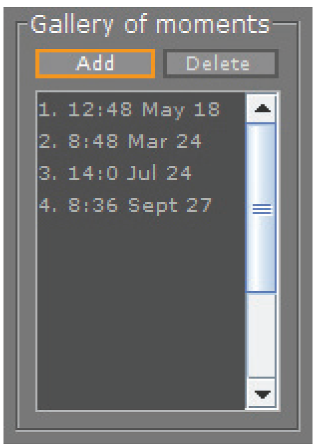


figure 4.10: Gallery Panel.

By default, the simulation is climate-based with renderings presenting the dominant sky condition for their representative moments. The user is also able to customize the sky type in the sky info panel (figure 4.5) and run simulations under four different weather conditions (clear, clear-turbid, intermediate, and overcast). This function helps the user to experience the range of daylighting conditions as a sequence over the whole year and be aware of the impact of the variation relating to the solar position, the sky condition, and the surroundings.

4.3.3 Comparison Panel

If the user finds some crucial moments for his design and would like to study the daylighting performance on a comparative basis while keeping track of design improvements for these moments, he can use the gallery panel (figure 4.10) in the left control panel to save any moment he is interested in during the interactive exploration of the temporal map and then load renderings of saved moments in the comparison panel (figure 4.11) for further analysis.

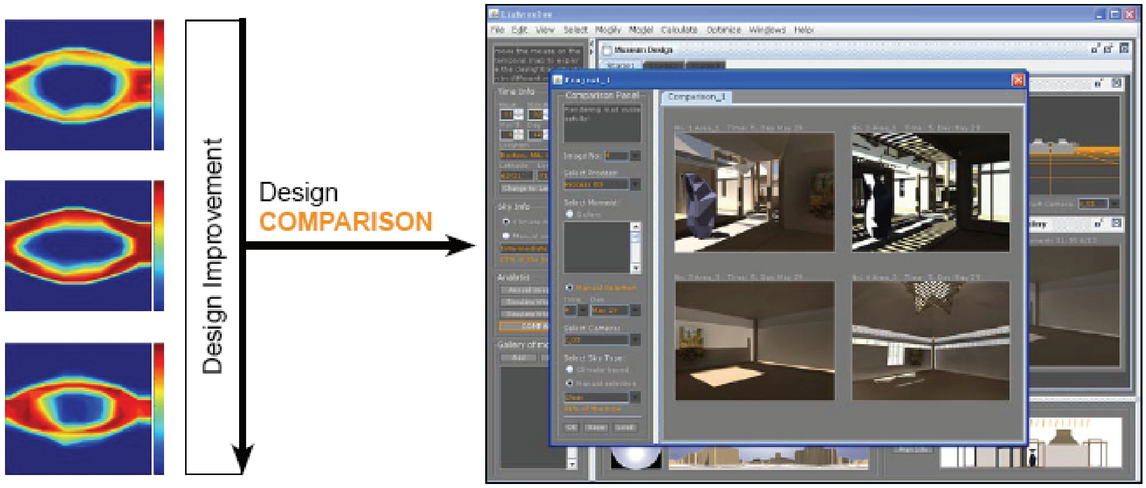


figure 4.11: Using comparison panel to conveniently compare different design solutions and keep track of the design improvement during the design process.

The moment selecting and saving process is very straightforward: when browsing the temporal map, the user simply needs to click on it at any position that represents his interested moment and freeze the cursor, then press “save” in the gallery panel to save the time information, the corresponding view for this AOI, and the dominant sky type. The cursor will be unfrozen by another click, and the user can continue his exploration. The whole interactive browsing will not be interrupted much by this moment saving process.

The comparison of renderings in the comparison panel is very flexible. After specifying which design iteration the rendering belongs to, the user can determine its representative moment either from the gallery or by doing a manual selection. The default rendering will present the saved view under the dominant sky type, though the user can also easily override the selected camera and sky information (figure 4.12) to check the visual effect for any other views and weather conditions. It provides a convenient platform to keep track of the design improvement during the whole design process for certain AOIs and allow the user to study the space’s performance for different AOIs in the same design stage.

figure 4.12: Comparison Panel.

Chapter 5

Platform Validations

5.1 Case Study of Current Tools

In order to have a better idea of how these tools work with the designer and how the way they transfer data influences the design process, we have performed two case studies based on existing buildings using tools from the two categories discussed before. Since within each category, programs have more or less similar features in terms of the available data output and data display, the author decided to choose two programs to do the case studies: one from the first category, the other from the second category. The options offered in terms of data representations, their popularity within the architectural design field and their user environment friendliness are all taken into account in the selection process.

As a famous rendering and modeling tool that has been widely used in the architectural field for a long time, 3D Max 8.0 was selected as the tool to represent the first category to do the case studies. Ecotect 5.5 was selected from the second category because it has sufficient quantitative analysis ability, a more user-friendly environment compared to other tools in its group, accurate qualitative photorealistic rendering ability provided by the embedded Radiance rendering engine, and its recent popularity in the architectural field.

Since the case studies focus on how the data transmission process between the program and the designer affects daylighting design, designs that have more specific daylighting requirements related to its functionality were selected, and buildings like museums and offices were seemed very good examples for this validation, with different but strict lighting requirements.

The Yale center for British Art designed by Louis Kahn (figure 5.1) was chosen as the museum case study. It requires a very evenly distributed illuminance level that has to be maintained within a range (e. g., 100lux to 200lux on walls for paintings) to provide enough lighting for viewing during the day and protect paintings from being damaged by too much heat gain from the light. The lighting environment should also provide good color rendering for all the exhibits. Therefore, daylight is a good choice for museum lighting in that it is rich during the day and it can provide very good color rendering compared to other lighting sources. Many innovative lighting components, such as the metal louver systems for the skylight (figure 5.2) and the wooden blinds used for the sidelight (figure 5.3), have been developed into to take the advantage of the natural light. In the case study, the exhibition room on the top floor illuminated by the skylight is selected as the tested area in 3D Max and Ecotect.

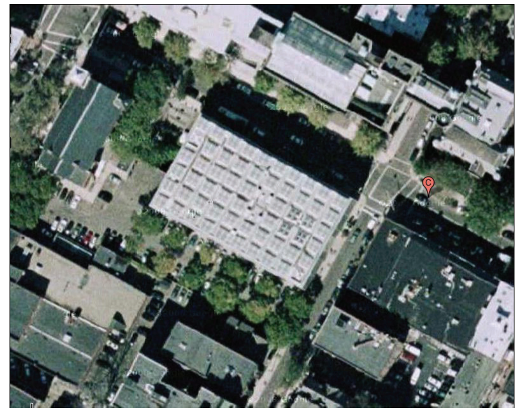


figure 5.1: Yale Center for British Art by Louis Kahn at New Haven, CT.
Center courtyard [Prown, 1977]

figure 5.2: Metal louver system created by Louis Kahn for Yale Center for British Art. [Prown, 1977]

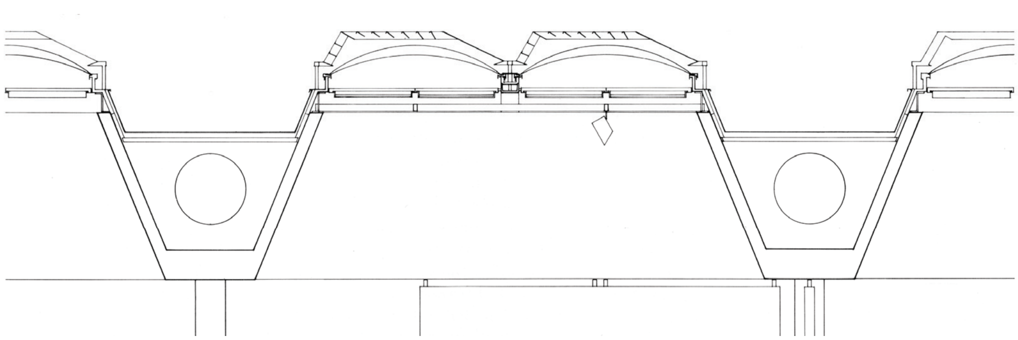


figure 5.3: Wood blind system created by Louis Kahn to translate direct sunlight to diffused light [Büttiker, 1994].

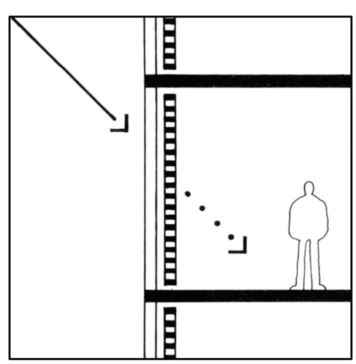


figure 5.4: Stata Center at MIT, Cambridge, MA.

The Stata Center at MIT (figure 5.4), a campus building with many irregular and curved shapes, was selected for the office case study. It also has specific lighting requirements. It has to provide the user inside the space enough light to read, write, perform precise tasks, etc. In addition, it needs to consider the visual comfort that can affect people's work, such as glare issues and high luminance contrasts between the interior space and the outside environment. Although electric light can easily provide an acceptable lighting environment according to the considerations mentioned above, using natural light is still desirable because of the energy saving, health benefits, and aesthetic consideration. The office room located on the third floor with south east glazing is the tested area.

5.1.1 Digital Model Preparation

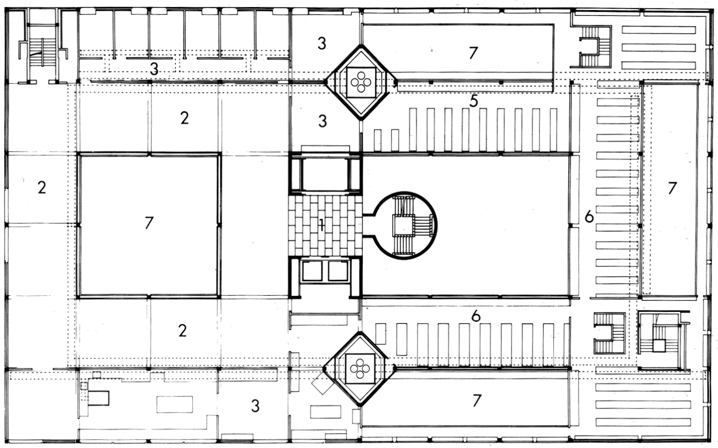
The main idea of this case study is to see in which way existing tools present the qualitative and quantitative data and whether the information transfer process is efficient and helpful for design decision making. Thus, the accuracy of the modeling, materials, and qualitative and quantitative calculation are not the main focus here.

1) Yale Center for British Art

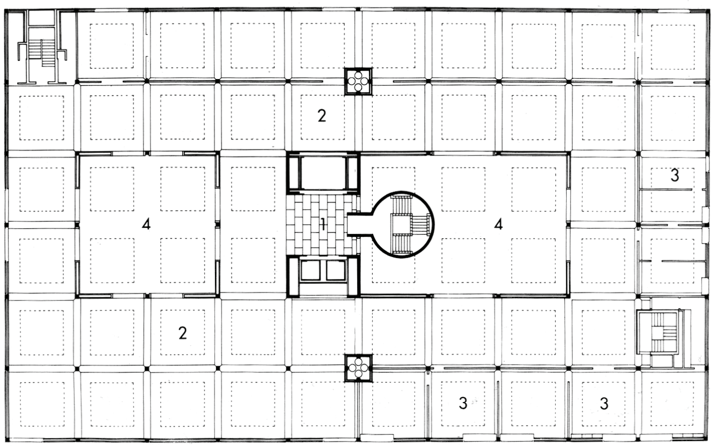
The digital model was constructed in SketchUp based on the plans and sections (figure 5.5 - 5.7) found in "Louis Kahn Yale Center for British Art" by Bruno J. Hubert and "Louis I. Kahn Light and Space" by Urs Büttiker. The model was then imported into 3Ds Max 8.0 and Ecotect 5.5 for further analysis.

The materials in this scene include white walls, wooden walls, concrete walls facing the interior courtyard and concrete ceiling structures, grey carpeting, and glazing used for the skylight. In 3Ds Max 8.0, except for the glazing, all material assignments were based on the built-in architecture material library. The glazing material assignment was based on the built-in Raytrace

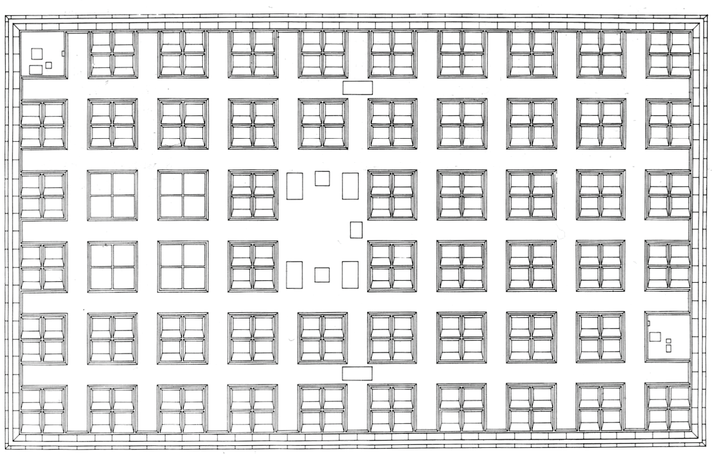
figure 5.5: Yale Center for British Art plans [Prown, 1977]:



Second floor



Third floor



Roof

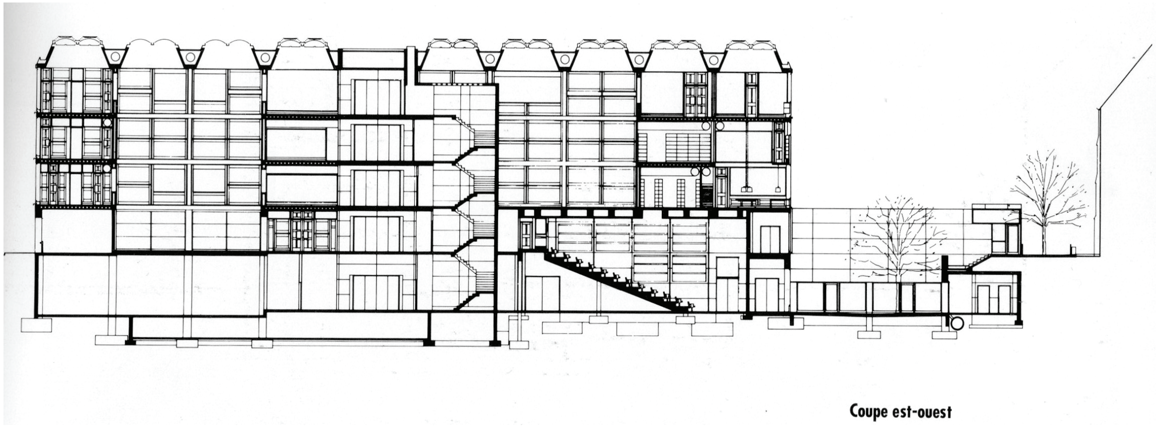


figure 5.6: Section of Yale Center for British Art [Prown, 1997].

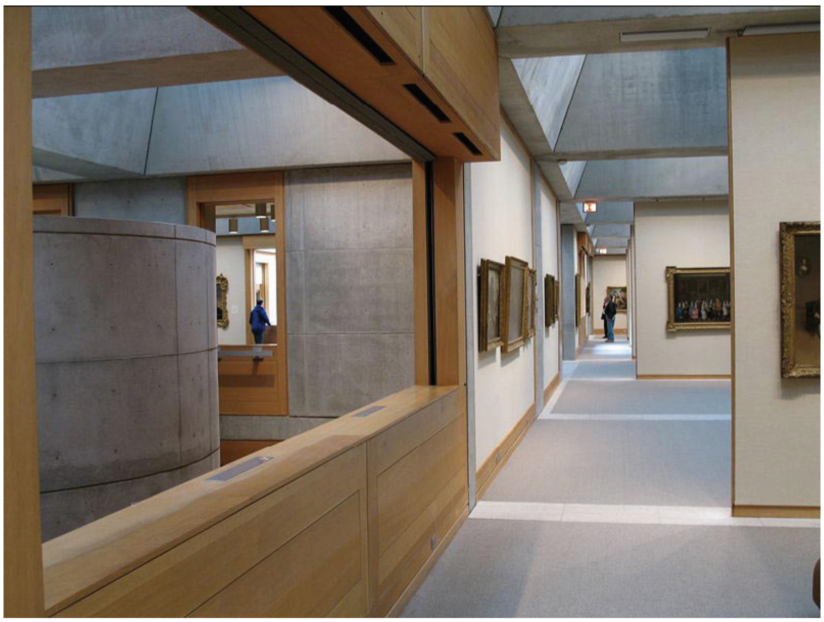
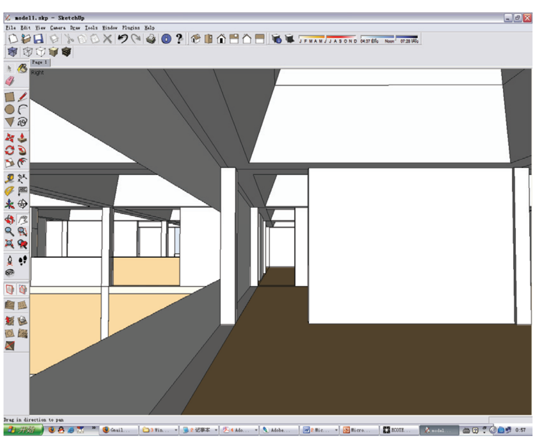


figure 5.7: Interior gallery room.



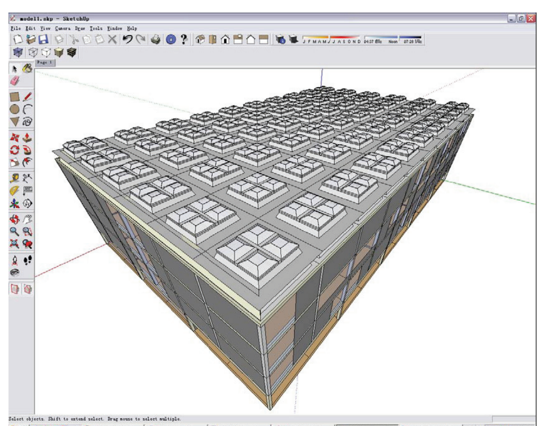


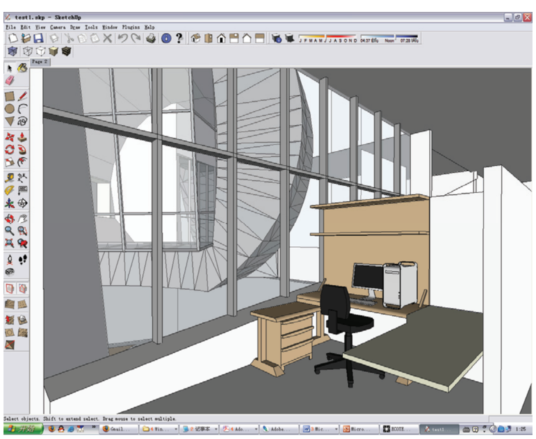
figure 5.8: Digital model built in SketchUp for Yale Center for British Art and the chosen viewport (left).

Material. The settings for each material are shown in Appendices 1. The camera is placed in the corridor close to the window facing to the interior courtyard (figure 5.8). In Ecotect, the camera setting is similar to that of 3D Max 8.0. Most of the materials come directly from the built-in library in Ecotect 5.5. The material setting is shown in Appendices 2.

2) Stata Center at MIT campus

The digital model (figure 5.9) for Stata Center Room 32-376 (figure 5.10-12) is constructed in SketchUp based on the original Stata Center 3rd floor CAD model provided by the research team in the RVSN group at MIT (Robotics, Vision, and Sensor Networks Group, http://rvsn.csail.mit.edu) who are currently working on the project “Ground-Truth, As-Built 3D CAD Model of Stata Center”. The digital model for this case study includes the tested office area and the surroundings close by (figure 5.9).

The materials in this scene include white interior walls, carpet floor, plywood panels used for dividing the working spaces, the plywood desk, the desktop, exterior specular metal surface facing to the office’s window, the glazing of the window in the tested office and the exterior adjacent building, and the rough metal window frame. As for material assignments for the Stata Center Room 32-376 in 3D Max 8.0, all materials come from the built-in architectural material library except for the glazing that is the built-in raytrace material. In Ecotect 5.5, materials directly come from the built-in library. The material settings for Stata Center in 3D Max 8.0 and Ecotect 5.5 are shown in Appendices 3 and Appendices 4. The camera points toward the south-facing glazing (figure 5.9).



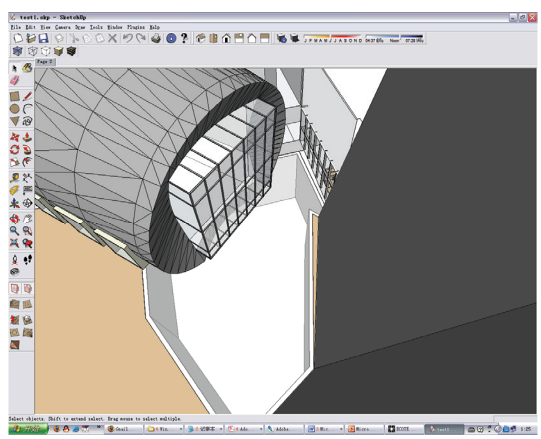


figure 5.9: Digital model built in SketchUp for Stata Center room 32-376.

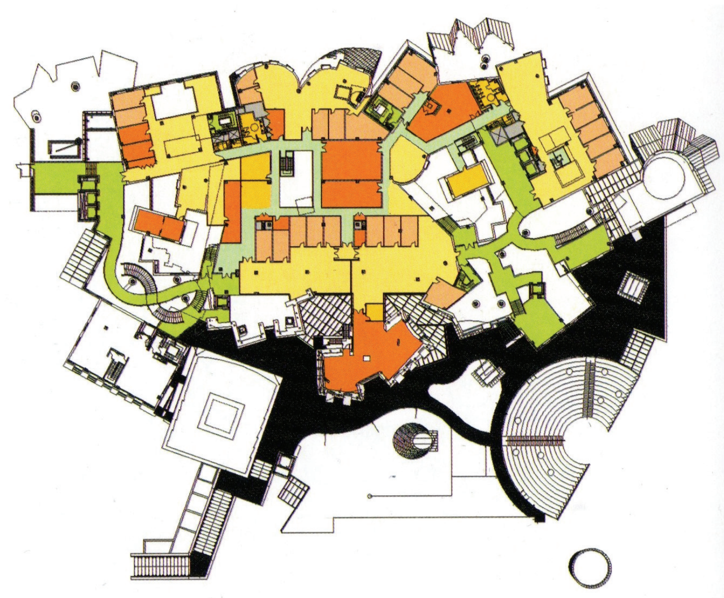


figure 5.10: Third floor of Stata Center [Joyce, 2004].

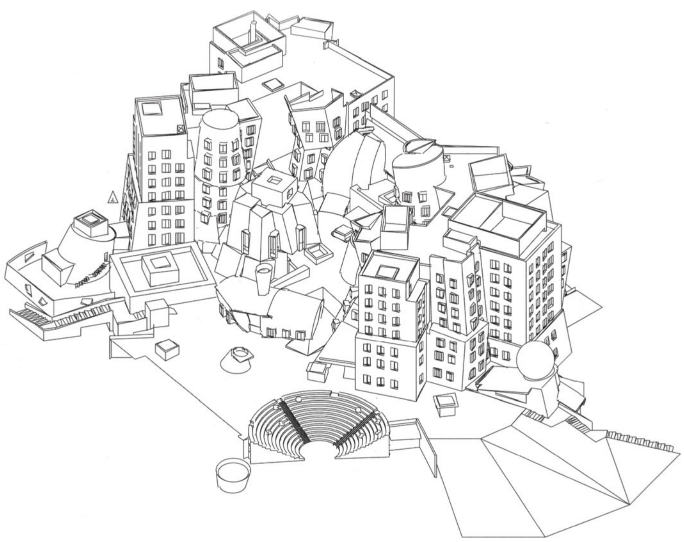
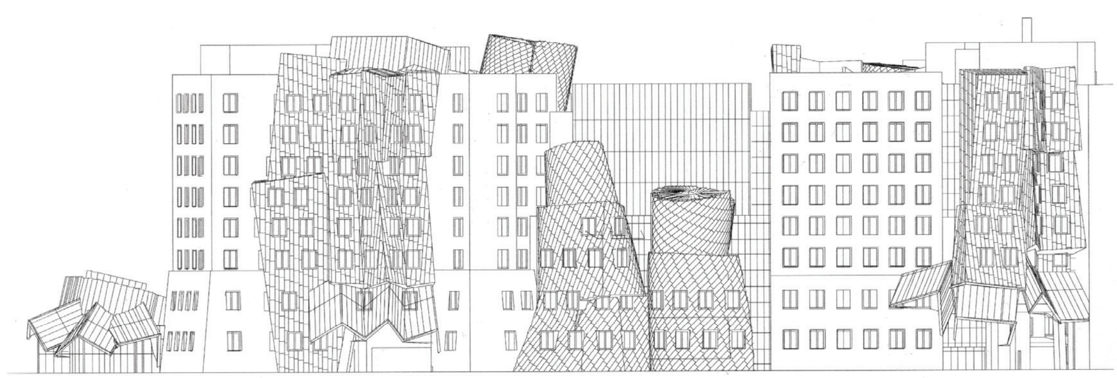


figure 5.11: Stata center axonometric view from the East [Joyce, 2004].

figure 5.12: Stata center elevation from Vassar Street [Joyce, 2004].



Vassar Street Elevation

5.1.2 Daylighting Analysis in 3Ds Max and Ecotect

In 3Ds Max 8.0, the user is able to get qualitative photorealistic renderings and quantitative illuminance and luminance false color renderings. Ecotect 5.5 provides more types of quantitative analysis, accurate renderings by Radiance engine, 3D sun chart for sun position and direct shadow analysis. In this case study, the author has performed all the available qualitative and quantitative analysis in 3Ds Max 8.0 and Ecotect 5.5 to make a comprehensive understanding of their data output and data transmission between the program and the designer.

a) Data switch

The author selected the advanced lighting – radiosity render engine to produce renderings in 3Ds Max. The radiosity calculation must first be performed, and then the user is able to choose a viewing angle for the generation of either photorealistic or false color renderings. The final rendering is displayed in a simple jump-out frame. In 3Ds Max 8.0, the process of generating qualitative realistic renderings and false color renderings proceeds is in sequence (figure 5.13).

Ecotect 5.5 allows the user to select any area he is interested in to perform quantitative daylight factor and daylighting level (illuminance) distribution analyses. In each calculation, it calculates one analysis grid. However, if the user wants to perform several grid analyses, he has to relocate the current grid and perform calculation again. The calculation result of the previous grid is lost and can never be viewed unless the user has saved an eco file for it. Thus, viewing quantitative grid analysis results for different areas within one design is a sequential and unrepeatable process in Ecotect (figure 5.13).

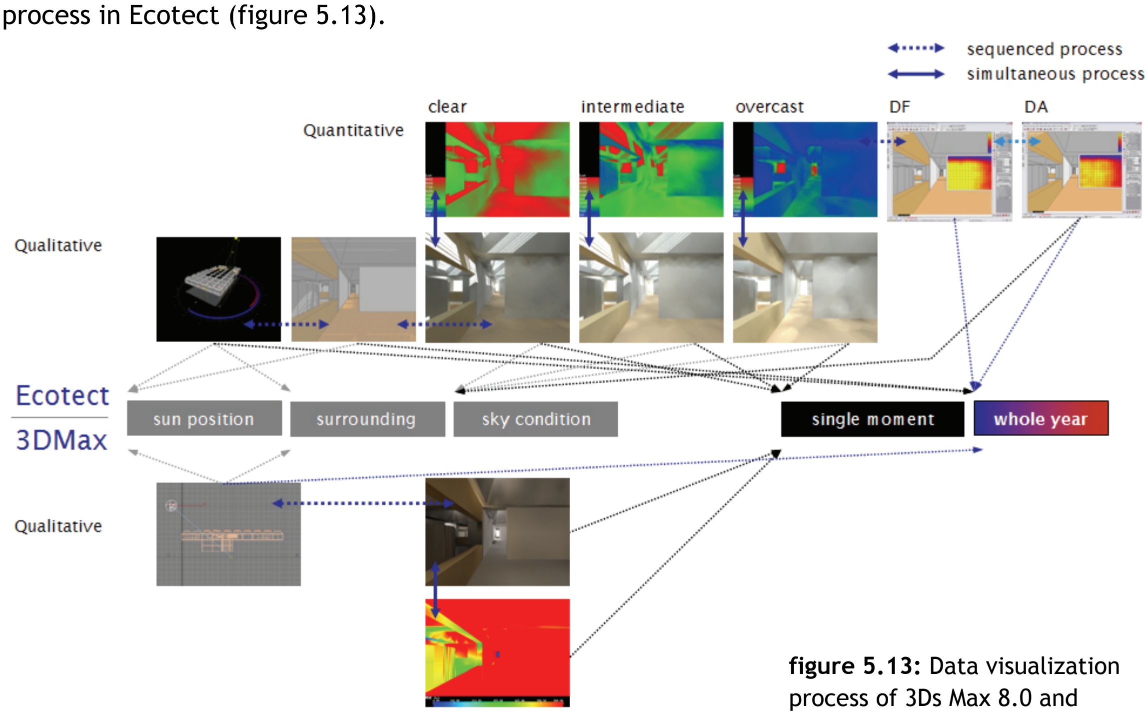


figure 5.13: Data visualization process of 3Ds Max 8.0 and Ecotect 5.5.

Ecotect can provide Radiance renderings that produce qualitative photorealistic output and quantitative false color outputs for illuminance and luminance. The Radiance rendering is displayed in Square One's Radiance image viewer (figure 2.21). This image viewer allows the user to load different types of data and layouts them in tab. In this case, the process of viewing realistic renderings and false color renderings can almost be considered simultaneous (figure 5.13). Because the user has to manually perform calculations for each rendering in advance and load the data himself, therefore, the process of viewing different types of data in Ecotect 5.5 still needs too much extra effort of the designer, and would interrupt the design process.

b) data output time variation

3Ds Max 8.0 provides the qualitative photorealistic rendering and quantitative false color rendering for one single moment in time (figure 5.13). In Ecotect 5.5, except for the daylight factor and daylighting level (illuminance) grid analysis, the qualitative photorealistic rendering and quantitative false color/contour line rendering is also for one single moment (figure 5.13).

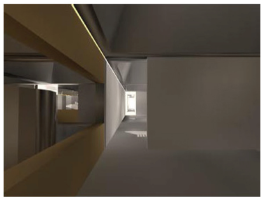
In addition, neither 3Ds Max 8.0 nor Ecotect 5.5 provides a guide or recommendation as to what kind of time the designer may need to look at. In this case, the designer may pick times randomly, based on his own experience, or from other daylighting-related handbooks. As discussed in the previous chapter, understanding the daylighting performance over the year is crucial for the designer to find out possible problems and make appropriate daylighting design improvements. In order to get an overall idea of how the space interacts with the daylight, the user needs to perform the daylighting analysis for several different moments over the year instead of simply looking at one single moment. In this case, the author selects 9 moments throughout the year based on the daylighting knowledge gained from the MIT 4.430 Daylighting Course. They are as shown in the table 5.1 below:

March 21st/September 21st	9:00am	12:00pm	15:00pm
June 21st	9:00am	12:00pm	15:00pm
December 21st	9:00am	12:00pm	15:00pm

table 5.1

3Ds Max 8.0: Photorealistic renderings for Yale Center for British Art (figure 5.14):

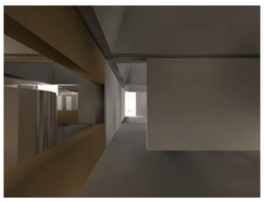
Mar/Sept 21: 9am



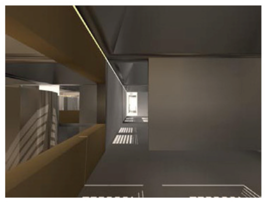
Mar/Sept 21: 12pm

Mar/Sept 21: 15pm

Jun 21: 9am

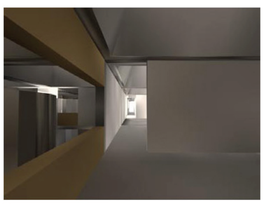


Jun 21: 12pm

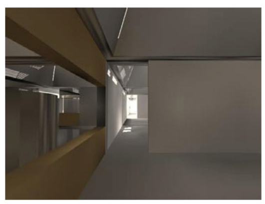


Jun 21: 15pm

Dec 21: 9am



Dec 21: 12pm

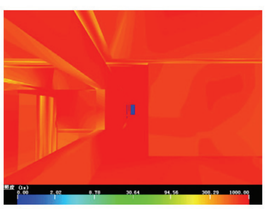


Dec 21: 15pm

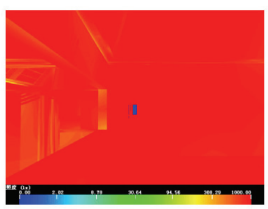
3Ds Max 8.0: Illuminance false color renderings for Yale Center for British Art (figure 5.15):

Illuminance false color renderings:
0-1000 lux

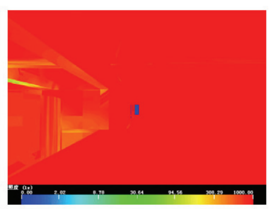
Mar/Sept 21: 9am



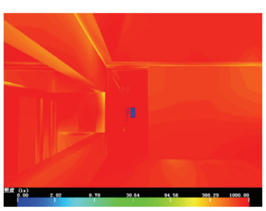
Mar/Sept 21: 12pm



Mar/Sept 21: 15pm



Jun 21: 9am



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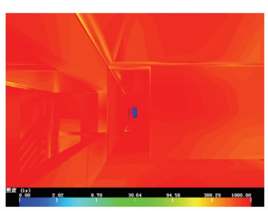

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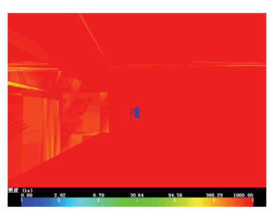

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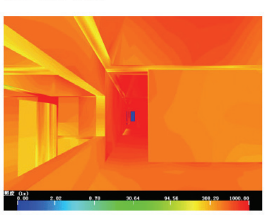

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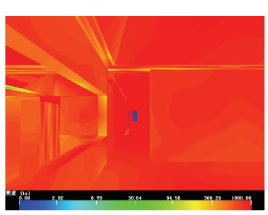
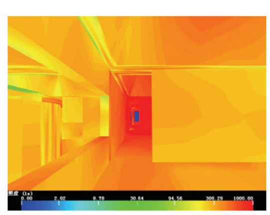
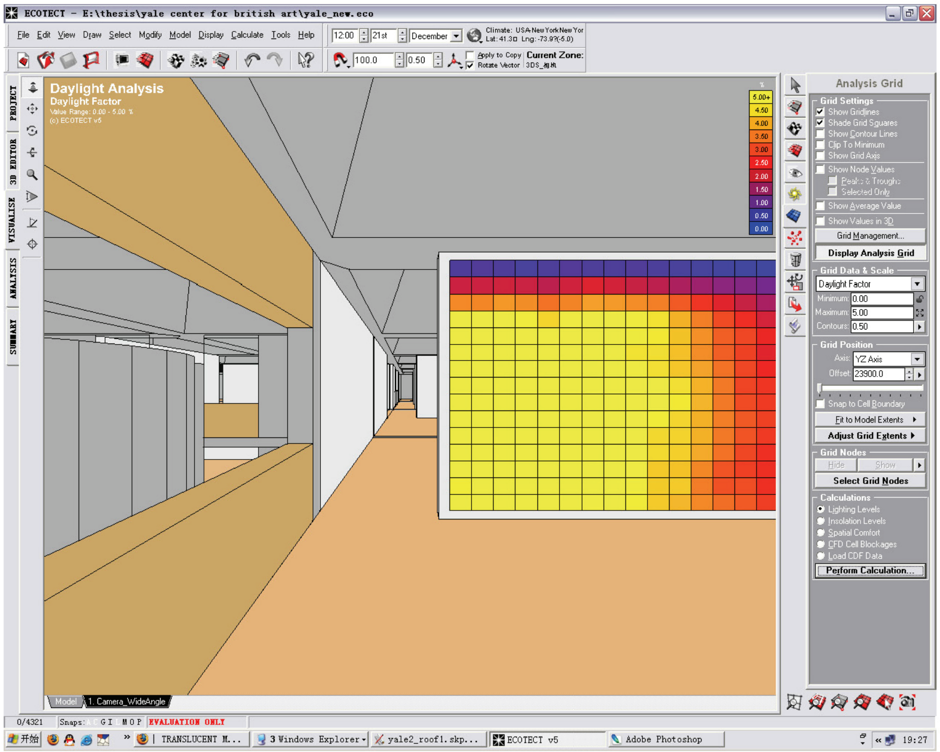


Dec 21: 15pm

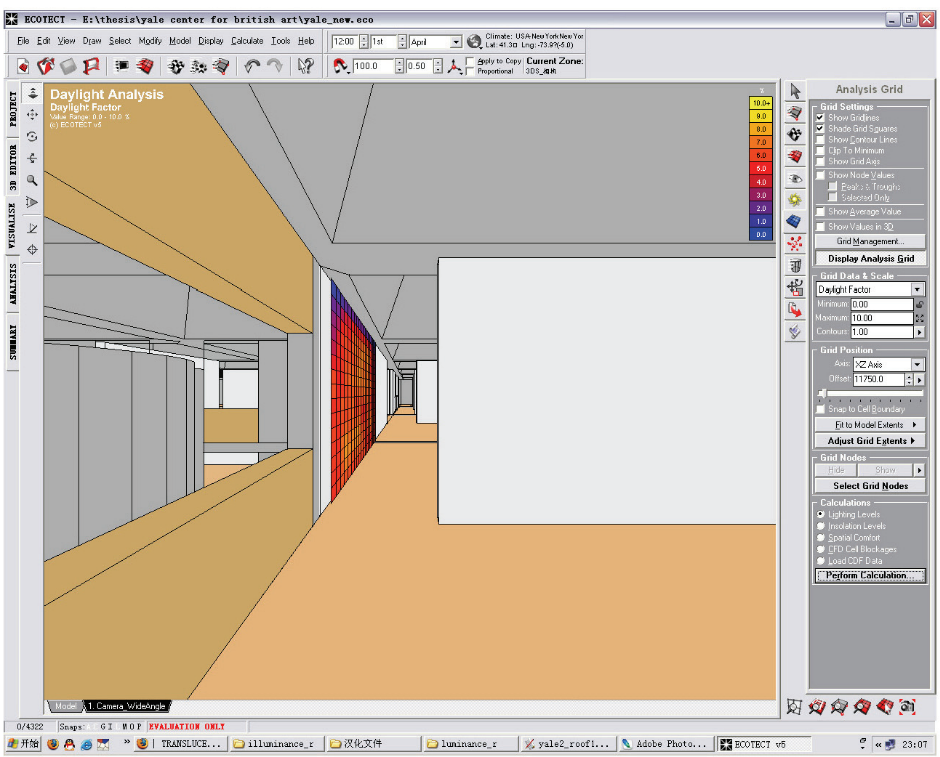


Ecotect 5.5: Daylight factor calculations for Yale Center for British Art (figure 5.16):

DF: 0-5.00%

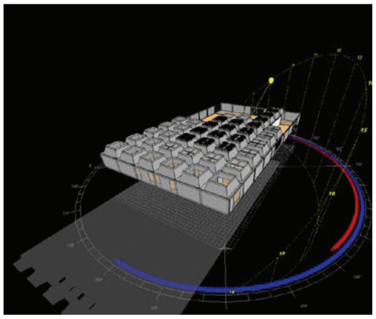


DF:
0-10.00%

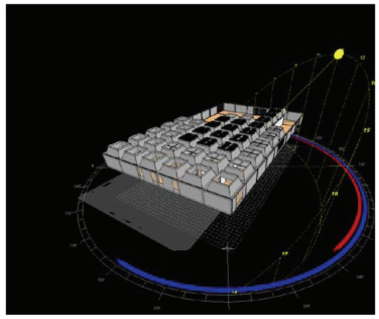


Ecotect 5.5: Sun Position Analysis for Yale Center for British Art (figure 5.17):

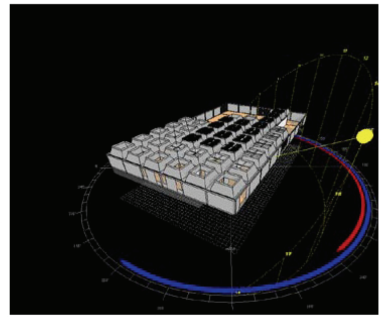
Mar/Sept 21: 9am



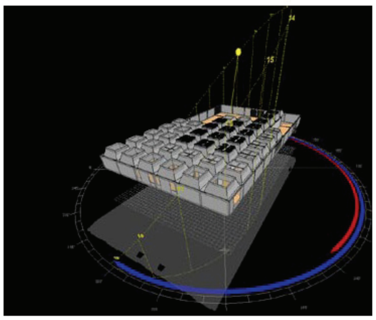
Mar/Sept 21: 12pm



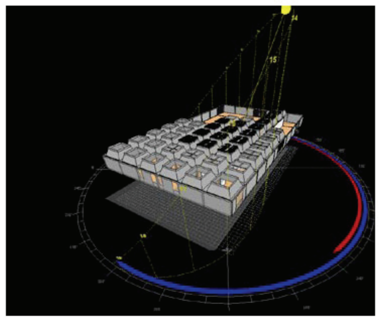
Mar/Sept 21: 15pm



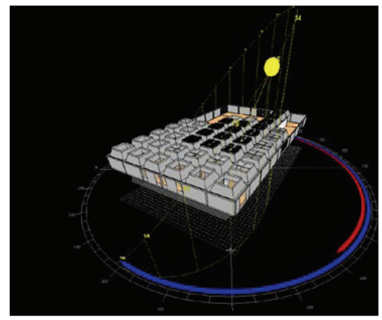
Jun 21: 9am



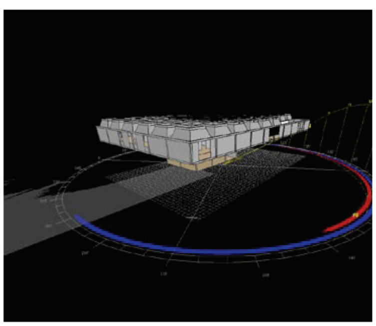
Jun 21: 12pm



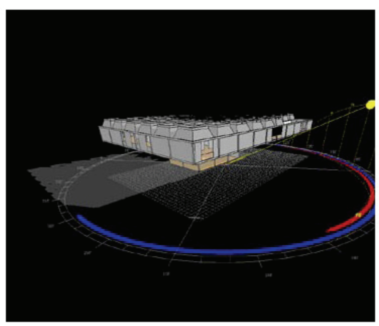
Jun 21: 15pm



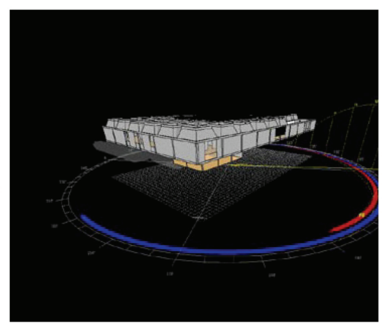
Dec 21: 9am



Dec 21: 12pm



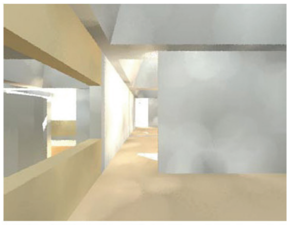
Dec 21: 15pm



Ecotect 5.5: Photorealistic renderings for Yale Center for British Art (figure 5.18):

Rendering under clear sky

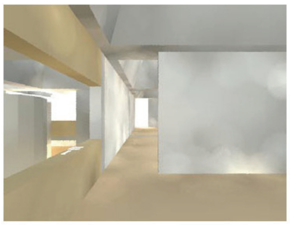
Mar/Sept 21: 9am



Mar/Sept 21: 12pm

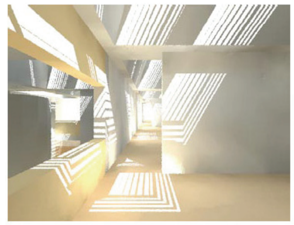
Mar/Sept 21: 15pm

Jun 21: 9am



Jun 21: 12pm

Jun 21: 15pm



Dec 21: 9am

Dec 21: 12pm

Dec 21: 15pm

Renderings under intermediate sky

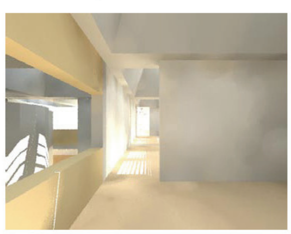
Mar/Sept 21: 9am

Mar/Sept 21: 12pm

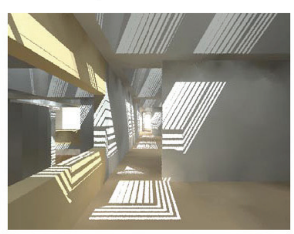
Mar/Sept 21: 15pm

Jun 21: 9am

Jun 21: 12pm



Jun 21: 15pm



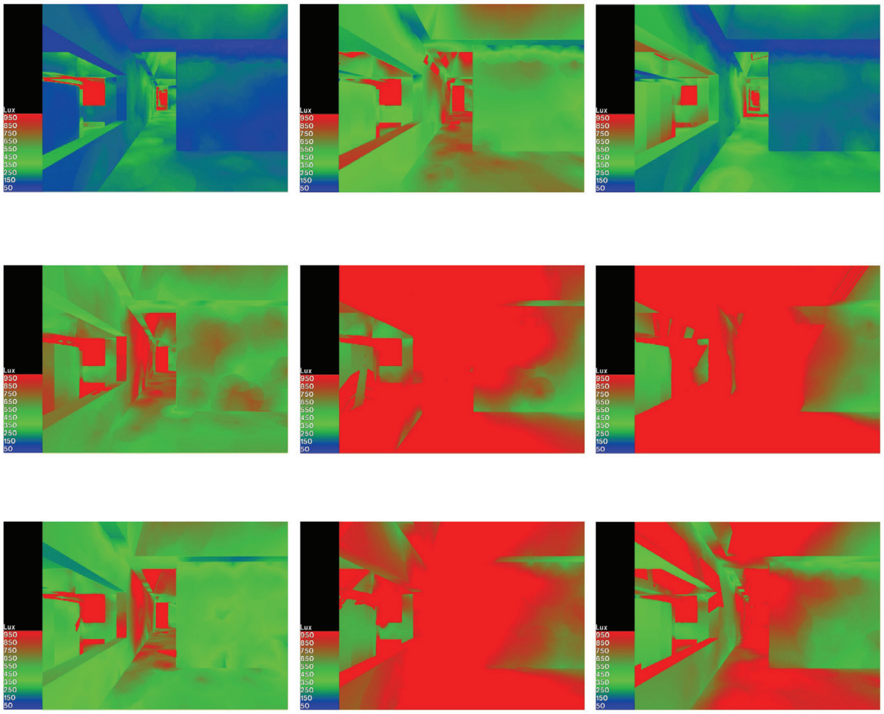
Dec 21: 9am

Dec 21: 12pm

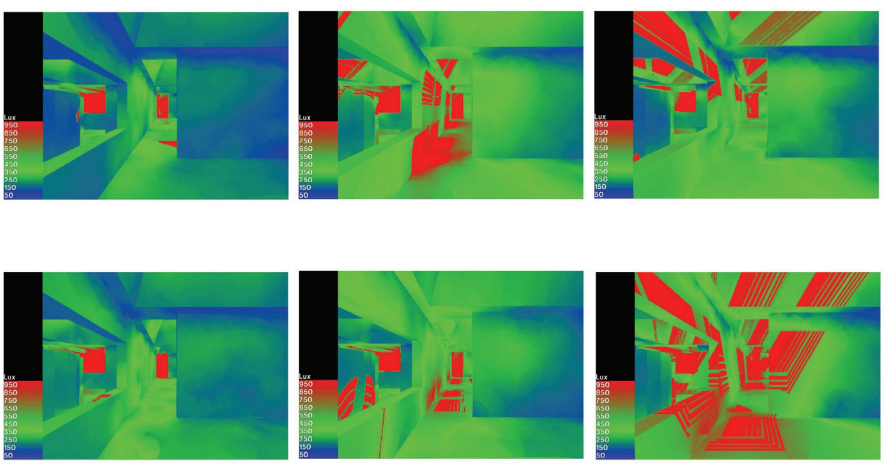
Dec 21: 15pm

Renderings under overcast sky

Ecotect 5.5: Illuminance false color renderings for Yale Center for British Art (figure 5.19):

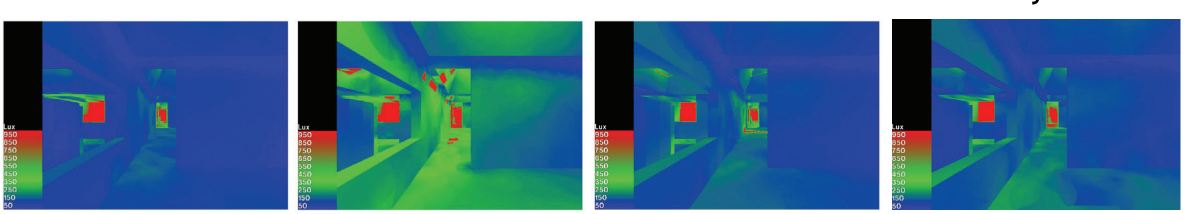


Rendering under clear sky
0-1000 lux



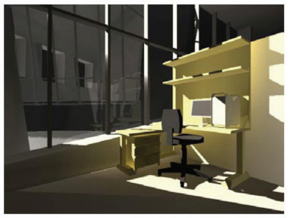
Renderings under intermediate sky
0-1000 lux

Renderings under overcast sky



3Ds Max 8.0: Photorealistic renderings for Stata Center Room 32-376 (figure 5.20):

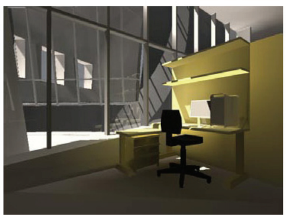
Mar/Sept 21: 9am



Mar/Sept 21: 12pm

Mar/Sept 21: 15pm

Jun 21: 9am

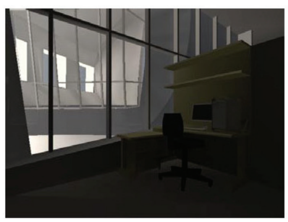


Jun 21: 12pm

Jun 21: 15pm

Dec 21: 9am

Dec 21: 12pm

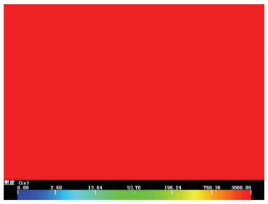


Dec 21: 15pm

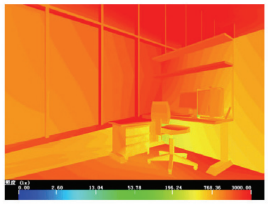
3Ds Max 8.0: Illuminance and luminance false color renderings for Stata Center (figure 5.21):

Illuminance false color renderings:
0-3000 lux

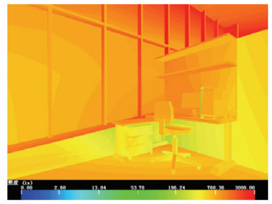
Mar/Sept 21: 9am



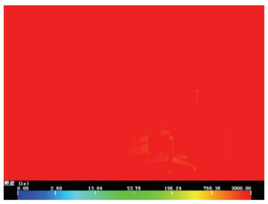
Mar/Sept 21: 12pm



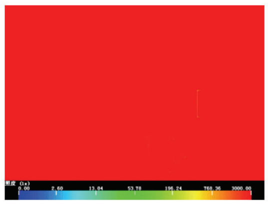
Mar/Sept 21: 15pm



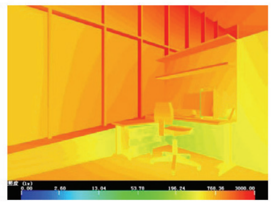
Jun 21: 9am



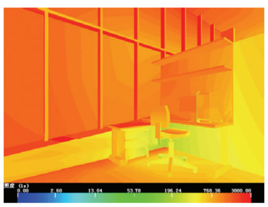
Jun 21: 12pm



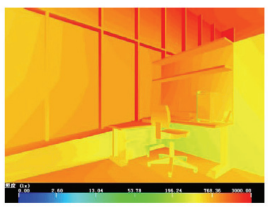
Jun 21: 15pm



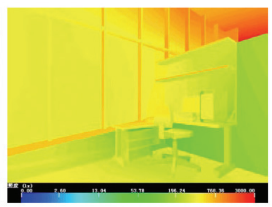
Dec 21: 9am



Dec 21: 12pm

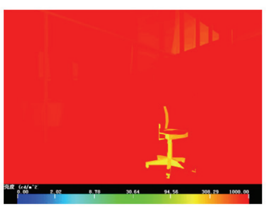


Dec 21: 15pm

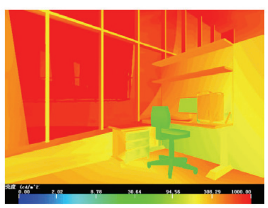


Luminance false color renderings:
0-1000 cd/m^2

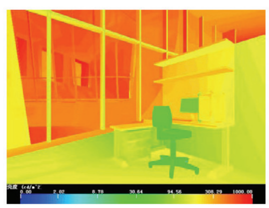
Mar/Sept 21: 9am



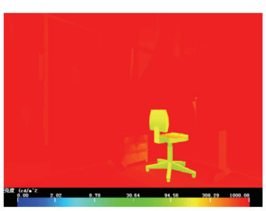
Mar/Sept 21: 12pm



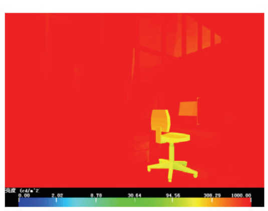
Mar/Sept 21: 15pm



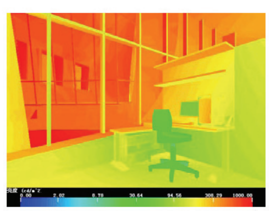
Jun 21: 9am



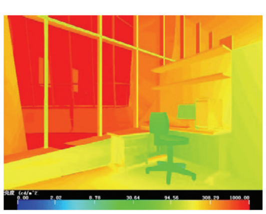
Jun 21: 12pm



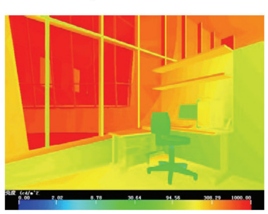
Jun 21: 15pm



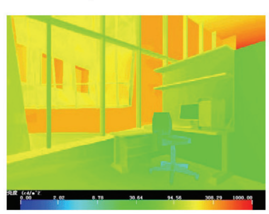
Dec 21: 9am



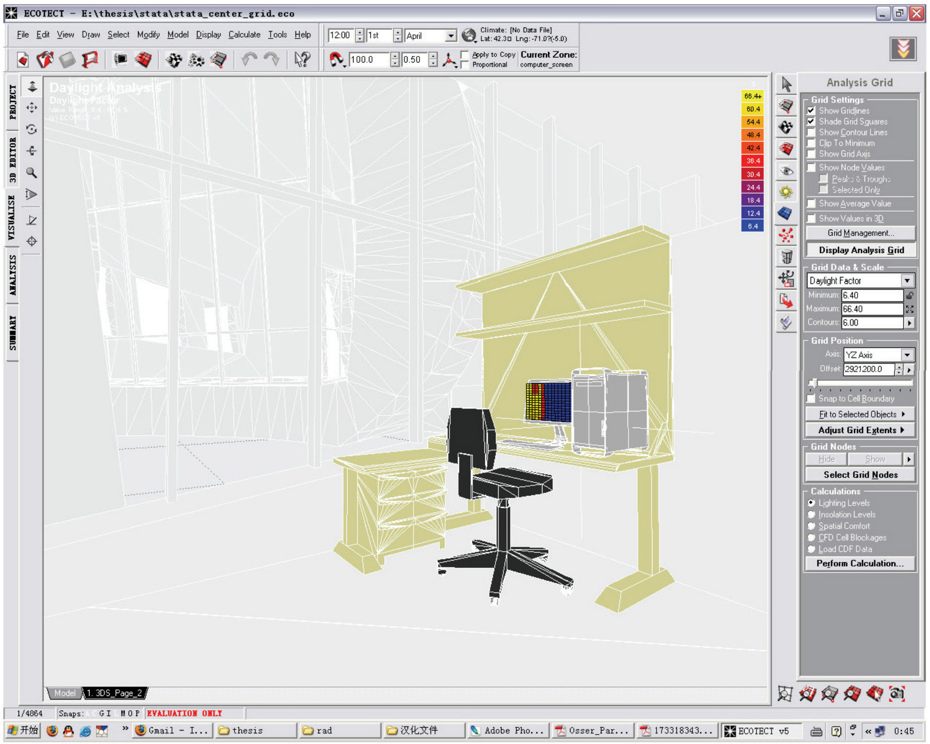
Dec 21: 12pm



Dec 21: 15pm



Ecotect 5.5: Daylight factor calculations for Stata Center Room 32-376 (figure 5.22):



DF: 6.4-66.4%

Ecotect 5.5: Sun Position Analysis for Stata Center Room 32-376 (figure 5.23):

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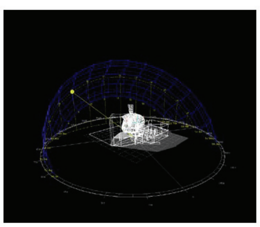

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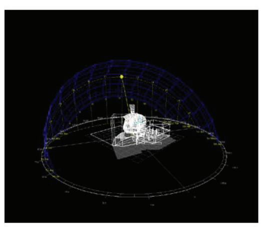

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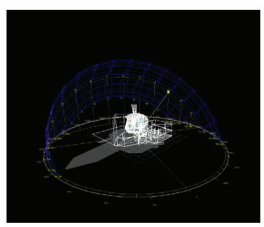

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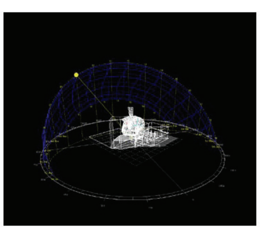

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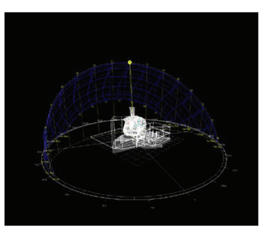

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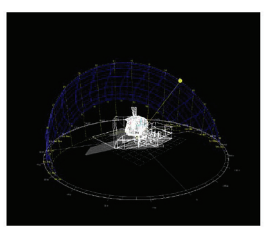

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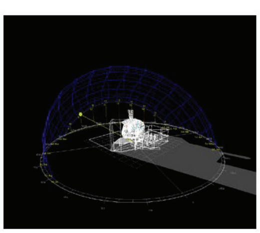

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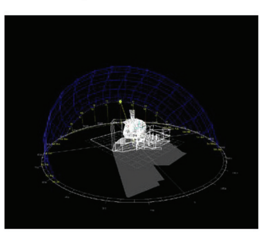

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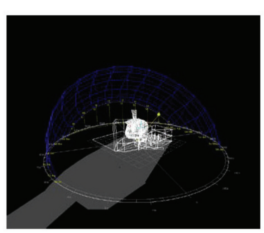
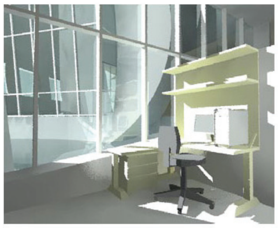


Ecotect 5.5: Photorealistic renderings for Stata Center Room 32-376 (figure 5.23):

Rendering under clear sky

Mar/Sept 21: 9am



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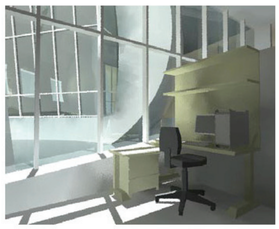

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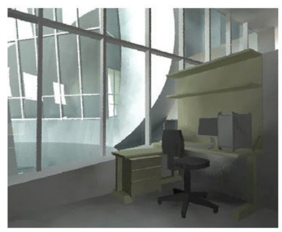
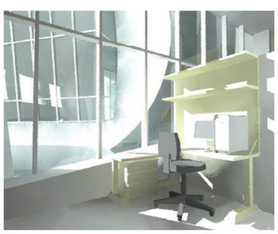


Renderings under intermediate sky

Mar/Sept 21: 9am



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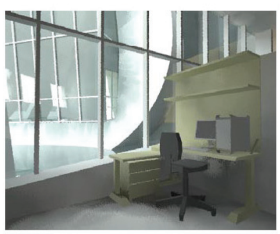

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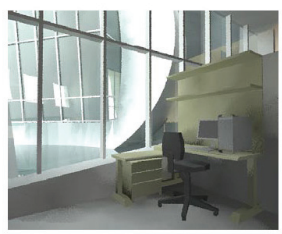

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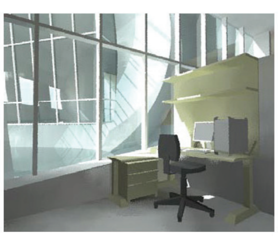

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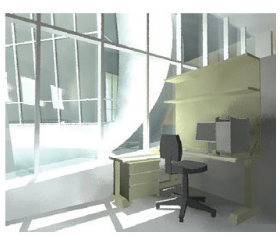

Jun 21: 15pm

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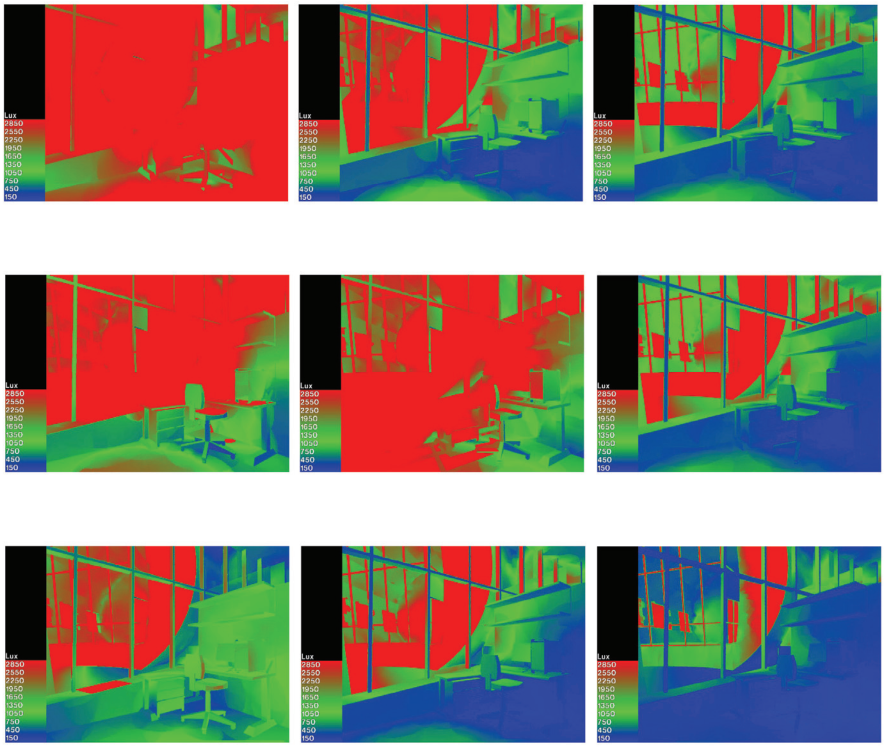
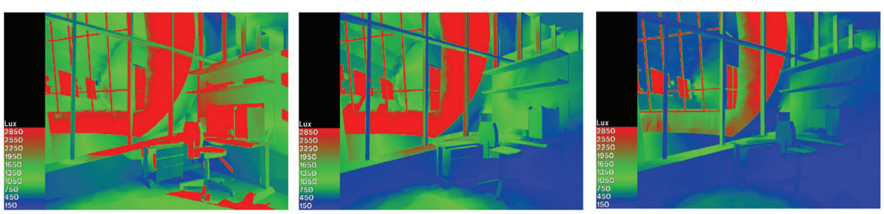
Dec 21: 15pm

Renderings under overcast sky

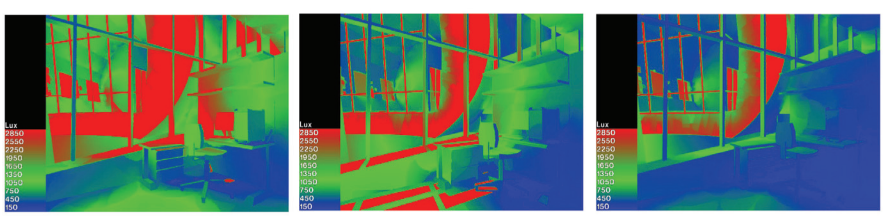
Ecotect 5.5: Illuminance and luminance false color renderings for Stata Center Room 32-376 (figure 5.24):



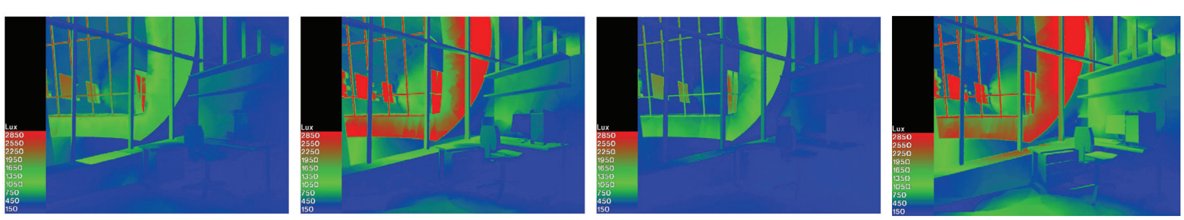
Illuminance false color renderings under clear sky:
0-3000 lux



Illuminance false color renderings under intermediate sky:
0-3000 lux



Illuminance false color renderings under overcast sky:
0-3000 lux



c) linking between data output and the outside environment

In 3Ds Max 8.0's data output display, there is no real link between the renderings and the sky condition and the physical surrounding. Ecotect 5.5 provides a very unique dynamic three dimensional sun chart (figure 5.13) to display the sun position at different moments and its movement over time. However, using this chart prevents the user from examining the interior space (figure 5.17, 5.23). In addition, no sky condition information is displayed with the rendering output. As in 3Ds Max, Ecotect has no real link between the daylighting performance and the sky condition and the surroundings (figure 5.11).

5.1.3 Existing Problems

As a typical modeling and rendering tool, 3D Max 8.0 does not have powerful and accurate quantitative daylighting analysis capabilities and the way of simultaneously presenting realistic renderings and false color images to assist the designer analyze them more efficiently. But for museum and office design, such as the Yale center for British art and the Stata center, simultaneously informed by the qualitative data and quantitative data simultaneously are in fact very important for the designer, and it is also important to understand the daylighting performance over the year to make sure the design has an acceptable annual performance.

Compared to 3D Max 8.0, Ecotect 5.5 has much powerful and more accurate quantitative analysis ability and qualitative photorealistic rendering. Although its Radiance image viewer (figure 2.21) provides a quick way to let the user check photorealistic renderings and false color renderings quickly, the designer has to put so much effort in loading all the data in advance, and it is apparently not a good way to view all these types of data for different moments without being easily confused by numbers of tabs.

In terms of linking the performance and outside lighting condition, both 3Ds Max 8.0 and Ecotect 5.5 do not really pay much attention. Although the sun ray displayed in 3Ds Max's modeling viewports shows the information of the sun position, it does not connect with individual renderings. Hence, for the designer's of the project like the Yale Center for British Art, where the architect most focus on designing innovative lighting components that effectively utilize direct sunlight at different times (figure 5.25). Ecotect has better performance in terms of analyzing direct sunlight, so it can assist designer to perform quick direct sunlight penetration analysis over the year. But it is difficult to dynamically linking this information with the sun movement, because there is no way to check the interior sun penetration while stilling having the 3D sun chart (figure 5.17, 5.23).

As for integrating weather variation into quantitative and qualitative data, they both do not support it. From analyzing data obtained from 3Ds Max, Frank Gehry may never notice that some spaces in the Stata Center have totally different daylighting behavior under clear skies and overcast skies, and this variation may cause uncomfortable experience for the space user (it will be discussed in the next validation). Ecotect has much better support of the sky condition definition; however, it still does not include the sky information with the analysis output, and the user cannot perform calculations based on the weather data of the site. Due to the fact that weather and sky conditions have a great impact on the daylighting performance, the lack of this important link in 3D Max and Ecotect data display platform brings great difficulty for the designer in linking the daylighting performance displayed and its related weather condition and adapt his design to the local weather variation.

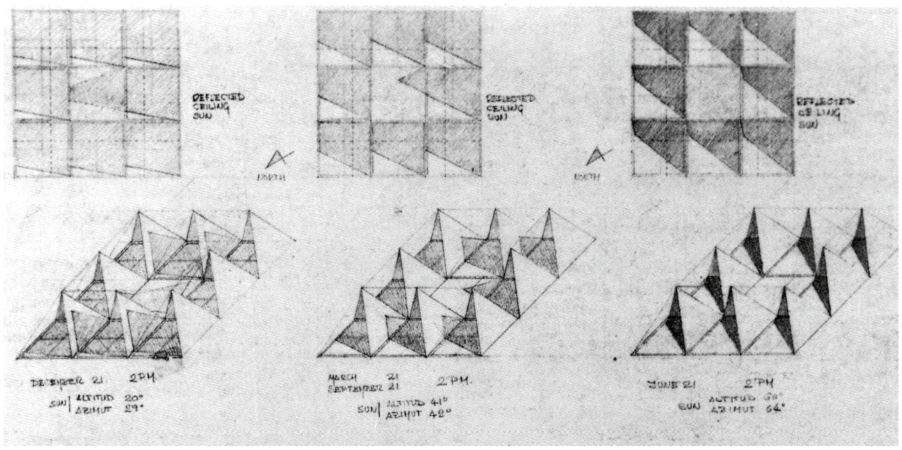


figure 5.25: Shadow analysis done by Louis Kahn for Yale Center for British Art [Joyce, 1977]

5.1.4 Data Visualization Comparison

In the case study for Stata Center Room 32-376, using either the rendering in 3Ds Max 8.0 or Ecotect 5.5 (figure 5.20, 5.23), it is not very straightforward to predict the potential glare problem on the computer screen simply by the rendering if the designer himself has no or little daylighting design experience. Even if he has enough knowledge to be aware of this problem, he has to check the false color renderings to find out the potential glare problem. Compared to these tools, the proposed data visualization platform can allow the designer to check the visual effect of the space while still noticing whether its performance from the temporal map (figure 4.4).

In existing tools, the author had to use her own daylighting knowledge to pick 9 moments to test the space performance over the whole year. For non professionals, it may cause serious problem for design decision-making if one relies only on the daylighting evaluations of arbitrary moments. However, in the proposed data visualization platform, the designer does not need to pick any moment in advance; it directly integrates information for the 56 moments over the whole year and allows the designer to access different moments easily using interactive browsing (figure 4.4). It avoids the potential situation that non daylighting professionals may neglect annual performance and only pick a few random moments for the daylighting analysis.

The author was also aware of the influence of weather in the interior performance, so every sky type is been chosen to perform tests for all 9 moments in Ecotect (3Ds Max 8.0 does not have real support for defining different sky conditions). From photorealistic and false color renderings (figure 5.20-5.24), which were viewed in sequence in these tools, the author found out that the glare issue caused by direct sunlight only happens under clear sky during the morning from Spring to Fall. However, there is no information which shows the variation of the local weather (Boston), it is hard to tell whether the glare issue will really happen at that period, because the weather might be cloudy for most of the time. There is also a problem of insufficient light for precise tasks (the space user needs to work on the robot very often) when there is no direct sunlight penetration displayed in renderings or when the sky is cloudy (figure 5.20-5.24). For the same reason, the author was not sure whether the possible overcast sky would bring more moments with insufficient light when the direct sunlight is supposed to come in.

Compared to these tools, the concern of potential environmental impact on the daylighting performance is already addressed in the proposed data platform. When the user is interactively browsing the temporal maps and informed by dynamically updated renderings, the corresponding dominant sky condition for that particular location is also displayed in the left control panel (figure 4.5) as a default. Besides this, the sky information is visualized as the sky dome and 360 degree surrounding renderings at the bottom of the platform. The user no longer needs to worry about how his design interacts with the real situation. By using the sky type manual selection function (figure 4.5), the user will not only be aware about the dominant weather condition but also the probabilities of other possible sky types at that moment and the impact of the surroundings. It can be greatly helpful when performing daylighting evaluation for space like Stata Center Room 32-376 where the sky condition and exterior space plays an important role of the interior daylighting performance.

In both 3D Max 8.0 and Ecotect 5.5, the quantitative and qualitative data are often displayed separately in a sequential way (figure 5.13). It can easily cause the designer to unconsciously focus on either the importance of achieving desired lighting level or the importance of nice visual effect. Both technical and aesthetic considerations are crucial for daylighting design, and the inefficient data transfer process in 3D Max and Ecotect makes it difficult to simultaneously evaluate interior space performance and exterior environmental variation. It is nearly impossible to realize some potential problems discovered here if the designer has little to no daylighting experience, since he may not choose the correct moments for evaluation and neglect the impact of the outside environment.

Instead of simply displaying data in most existing daylighting simulation tools, the LightSolve data visualization platform proposed in this thesis places more emphasis upon how to present and deliver quantitative and qualitative data to the user so that the user can comprehensively understand all the information and be aware of the potential relationship among daylighting performance, the space design, and the outside environment. It closely links quantitative temporal maps and qualitative renderings, with the purpose of visually aiding the user in better understanding the quantitative output. More importantly, the natural environmental impact on the building's performance is emphasized greatly in this platform; therefore, the user is able to focus on refining their design while still taking into account the environmental influence on it in a convenient way.

5.2 Demo Museum Design informed by Proposed Data Visualization Method

The proposed data visualization platform for LightSolve aims to create a successful data transmission between the program and the designer so as to inform the design process in a more efficient and intuitive way and support the designer in making appropriate design improvements. A demo museum design is developed in SketchUp and analyzed with this platform using the LightSolve algorithm to test whether the proposed platform reaches its objective. Since the render engine which will be used for generating temporal maps and renderings is now being developed at the Department of Computer Science at Rensselaer Polytechnic Institute in New York, leading by Professor Barbara Cutler, all the data presented in this validation test are currently pre-computed with Radiance and 3D Max; the temporal map is produced with Radiance, and the rendering is produced with 3D Max 8.0.

5.2.1 Initial Design

Concept:

The hypothetical location of this demo museum design is in Boston. The basic concept is to use natural light to illuminate the museum's interior space and provide appropriate lighting level for paintings and sculptures. The author decided to use skylight as the major lighting resource with few side openings so as to obtain enough natural light directly from the unobstructed sky and maximize the area of the exhibition walls for paintings.

The exhibition area is composed of four similar rectangular elements with center skylights and side skylights adjacent to the walls (figure 5.26-5.27). Based on personal experience, the author thought this skylight arrangement is able to provide pleasant diffused natural light for the paintings on the interior walls. These four gallery rooms are connected by two fully open courtyards and two partial open corridors (figure 5.26-5.27). The corridors (figure 5.28) are selected as exhibition areas for sculptures, because the author thought that the daily motion of the Sun from east to west can bring much more direct sunlight to this area than the other two courtyards (figure 5.29). Each gallery room has one narrow side window, facing to the open courtyards (figure 5.29) for the purpose of view and maximizing the exhibition area on the wall. A wooden arbor (figure 5.30) stands at the center of these corridors and courtyards and interacts with the direct sunlight to form diverse shadow effects and make the space more interesting. Four other similar arbors are set at each entrance of the museum; their purpose is to visually break the solid exterior walls with the vacant wooden structure (figure 5.29-5.30) and its shadows and create a rhythm of the elevation views.

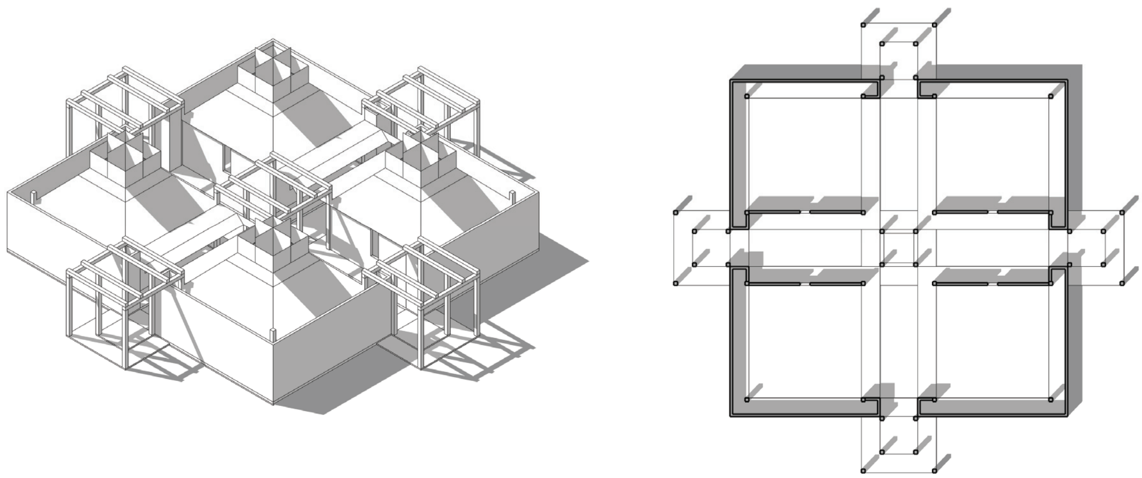
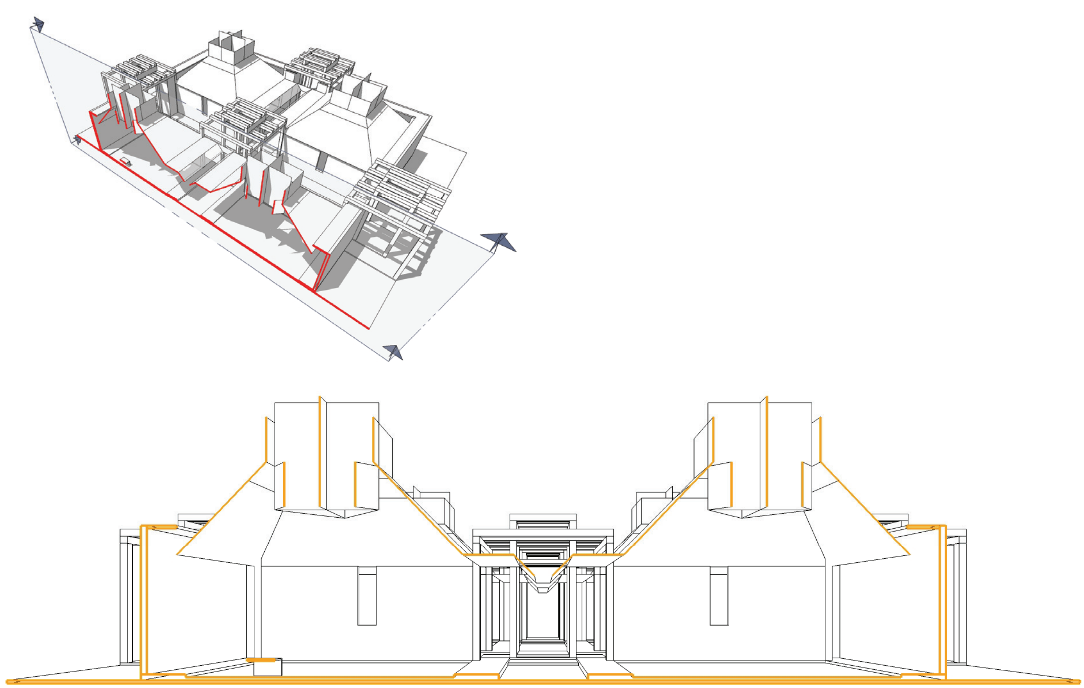


figure 5.26: Demo Museum - Axonometric view from the East South (left) and plan view (right).

figure 5.27: Demo museum sections.



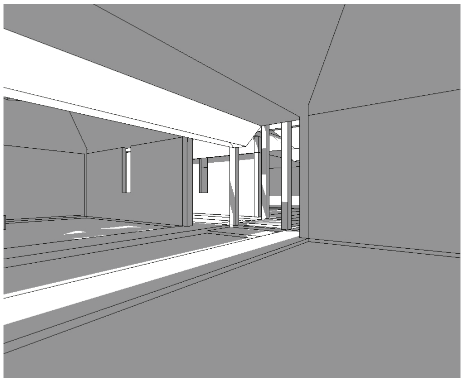


figure 5.28: Open corridor.

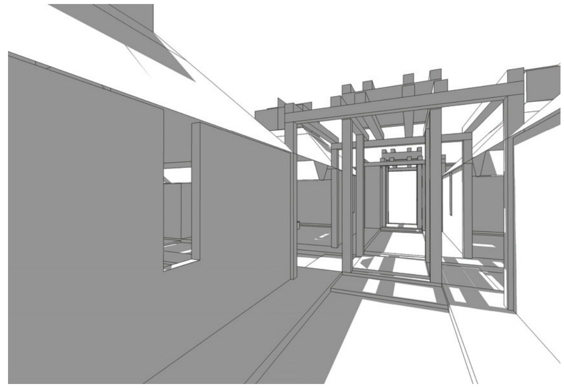


figure 5.29: Inner courtyards

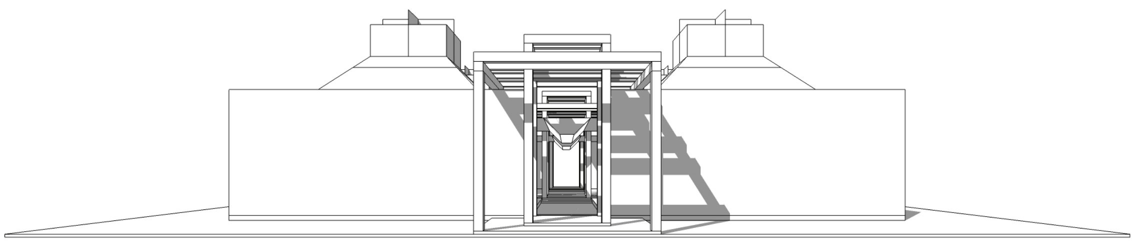


figure 5.30: South elevation.

A digital model for this initial design was constructed in the SketchUp. Hypothetical surroundings (figure 5.31) were also constructed based on a real case of a campus area. In order to test whether this design was able to reach its initial goals, the author decided to use LightSolve to run a daylighting evaluation. Three AOIs (table 5.2) have been selected and assigned different design goals to perform the analysis:

AOI_1	open corridor with skylight	
	GOAL:	get direct sunlight for sculptures
AOI_2	exhibition work planes	
	GOAL:	get enough light for the exhibited things
AOI_3	North and East walls for paintings in the North East gallery room	
	GOAL:	1. get enough light for paintings 2. avoid direct sunlight hit onto paintings 3. avoid too much light on paintings (< 200 lux)

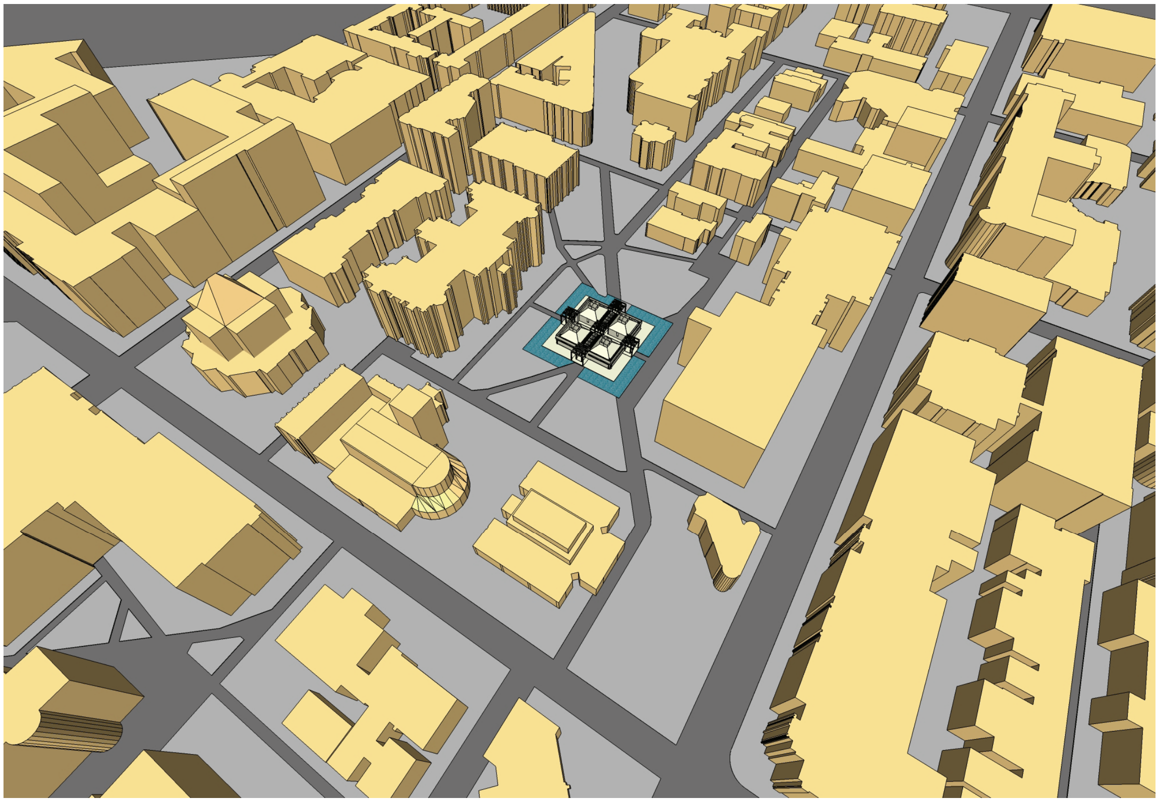


figure 5.31: Hypothetic surroundings.

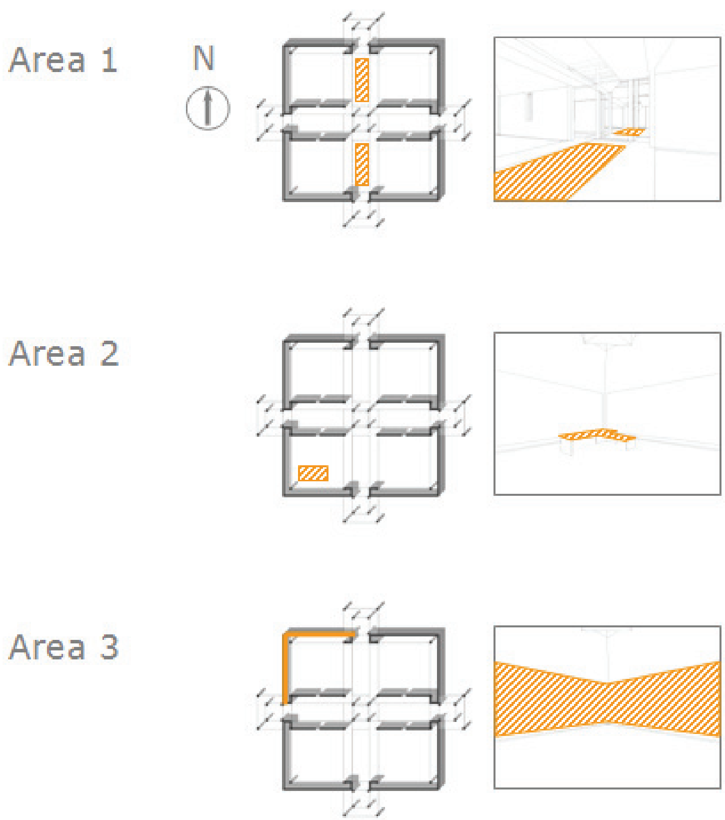


figure 5.32: Chosen AOIs for daylighting analysis.

As mentioned at the beginning of this chapter, the analysis results displayed in the proposed data visualization platform were currently pre-computed. Temporal maps were produced in Radiance by the PhD student Siân A Kleindienst in Building Technology Program at MIT Department of Architecture. Renderings were generated in 3D Max 8.0 by the author.

Analysis Results Presented in the Proposed Data visualization platform:

At the first glance, the author found out there was large areas of blue on the temporal maps (figure 5.33) for the last two AOIs (exhibition work planes and North East gallery walls) during the year. It meant the daylighting performance of these AOIs did not reach their goals defined by the author within these periods represented by the blue color. The exhibition work planes only have good daylighting performance early in the morning and late in the afternoon (figure 5.34), and the NE walls (North East gallery walls, the author will use NE walls to represent it in the rest of this thesis) has bad performance from around 9am to 3pm except for during the winter (figure 5.34). The first AOI, the open corridor, has much better performance than the others. It has acceptable performance for most moments during the daytime, but it still did not meet its goal from October to the end of the year (figure 5.34). From the temporal maps, the author got an overall idea of the design's performance and decided to use the interactive browsing to see what happened in the museum during those good and bad moments.

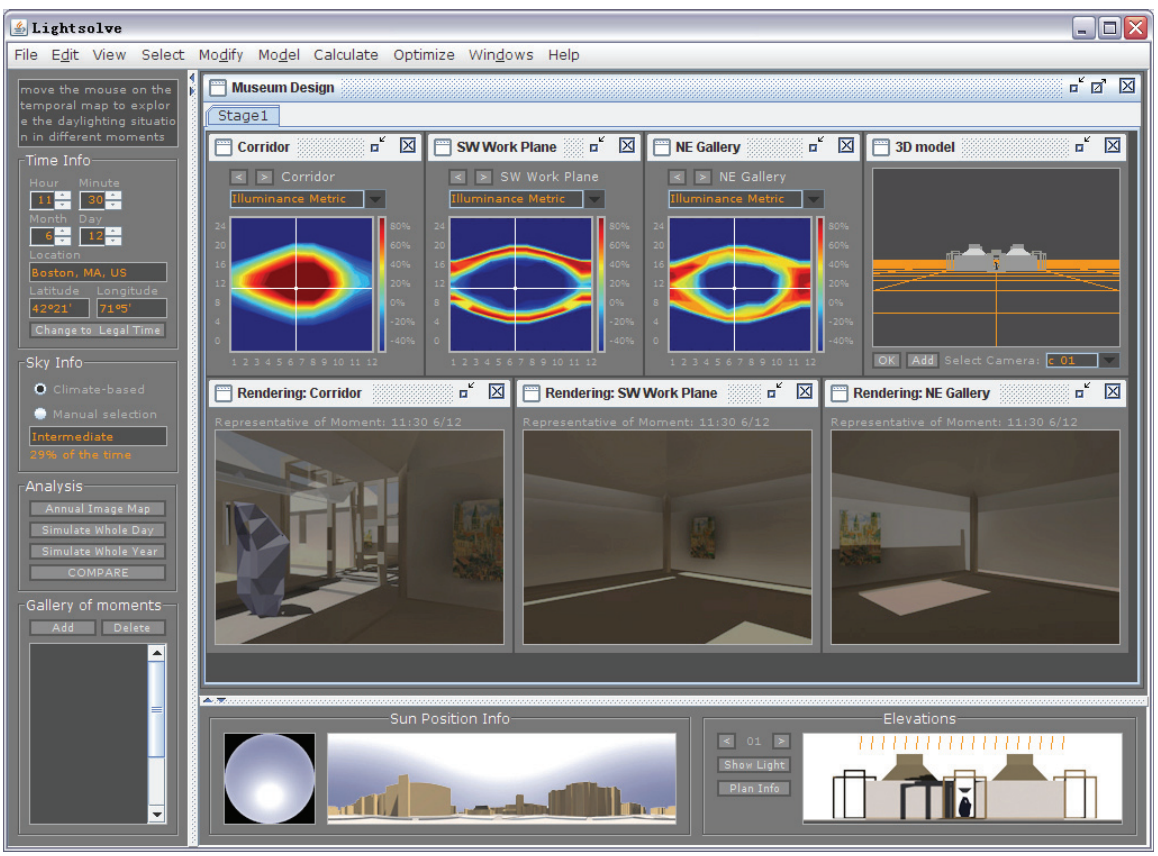


figure 5.33: Analysis result for the initial design presented in the proposed data visualization platform.

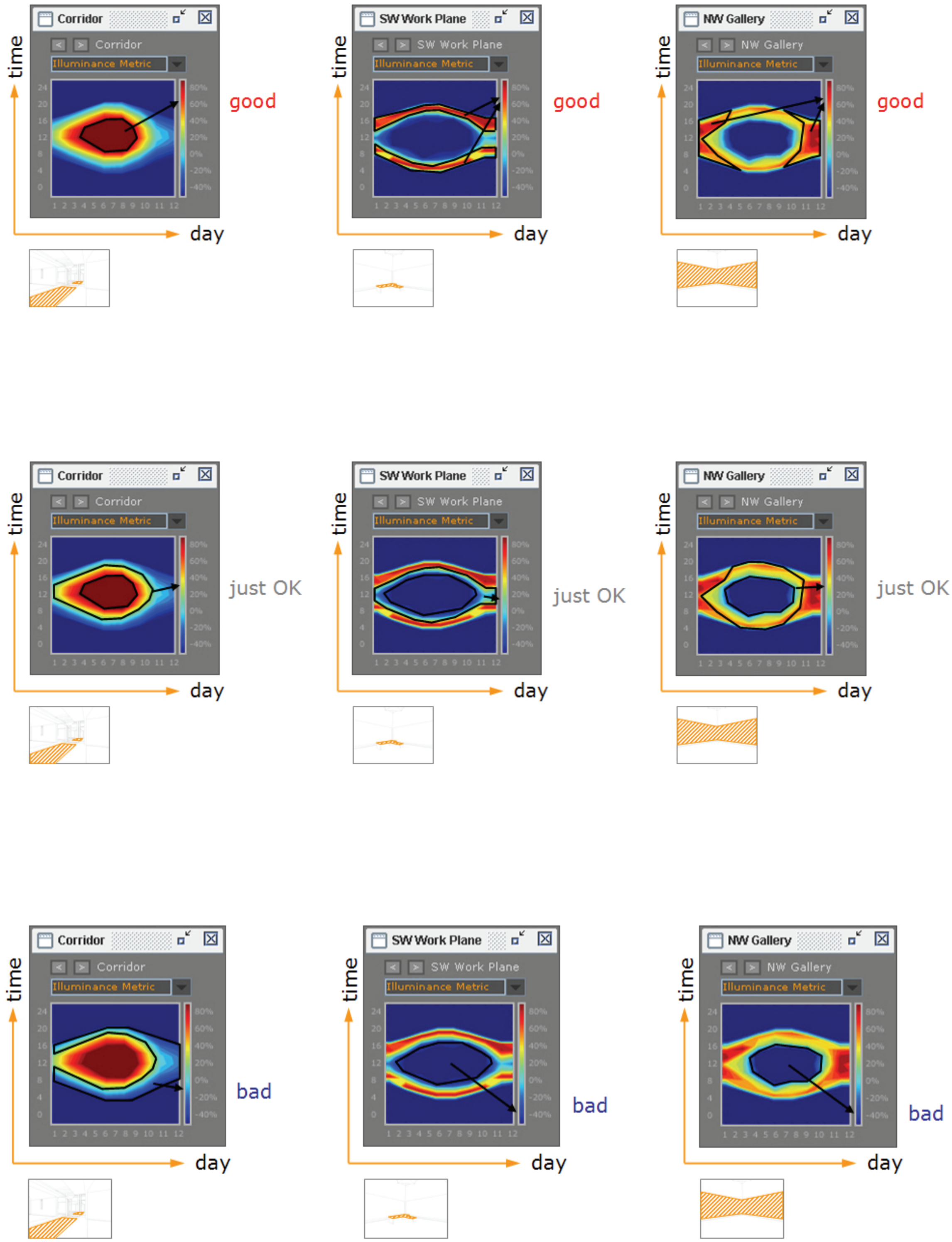


figure 5.34: Good (top), Just-OK (middle), Bad (bottom) moments on temporal maps.

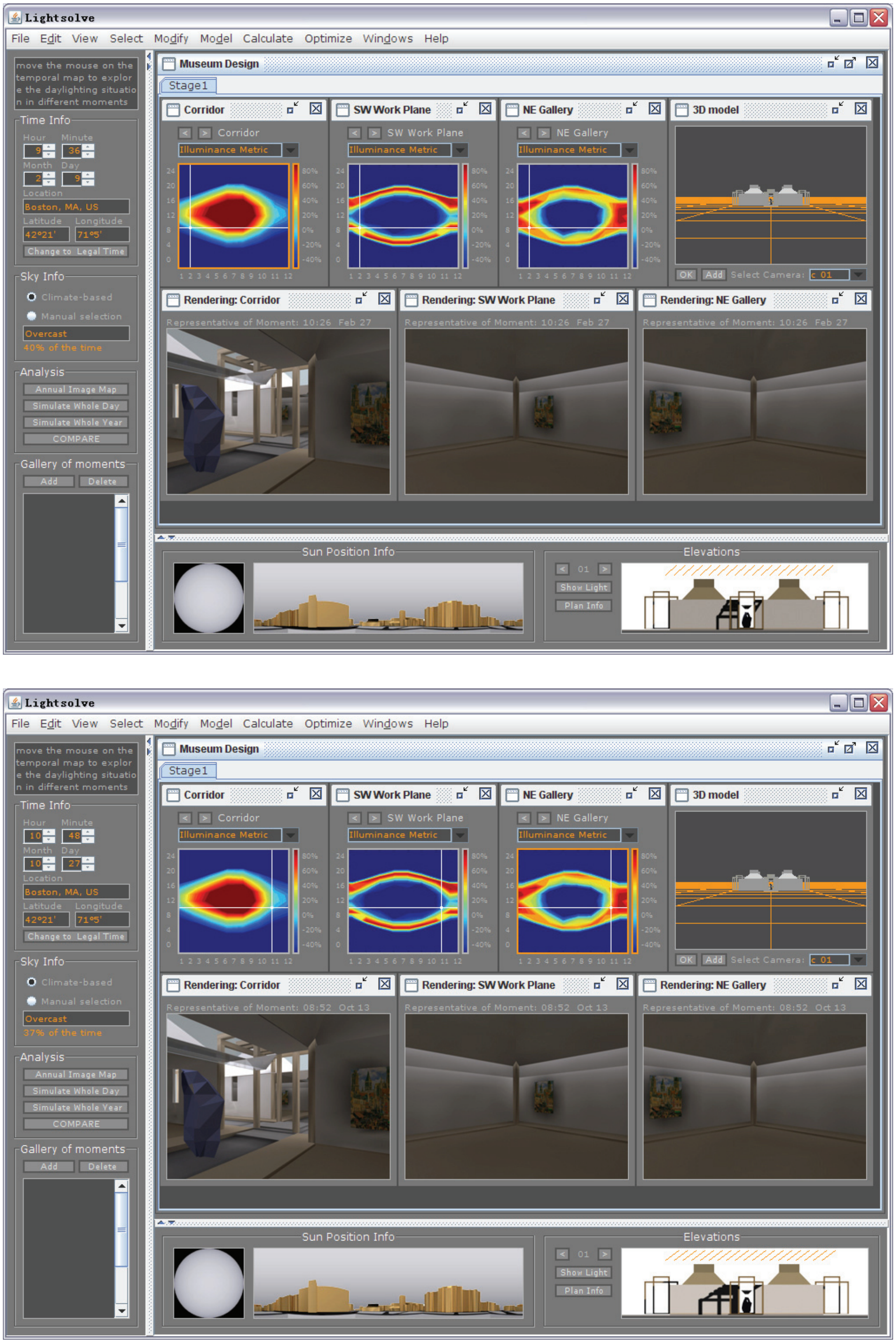


figure 5.35: Moments that the sky condition is most likely overcast. Bad for corridor, but good for SW work planes and NE walls.

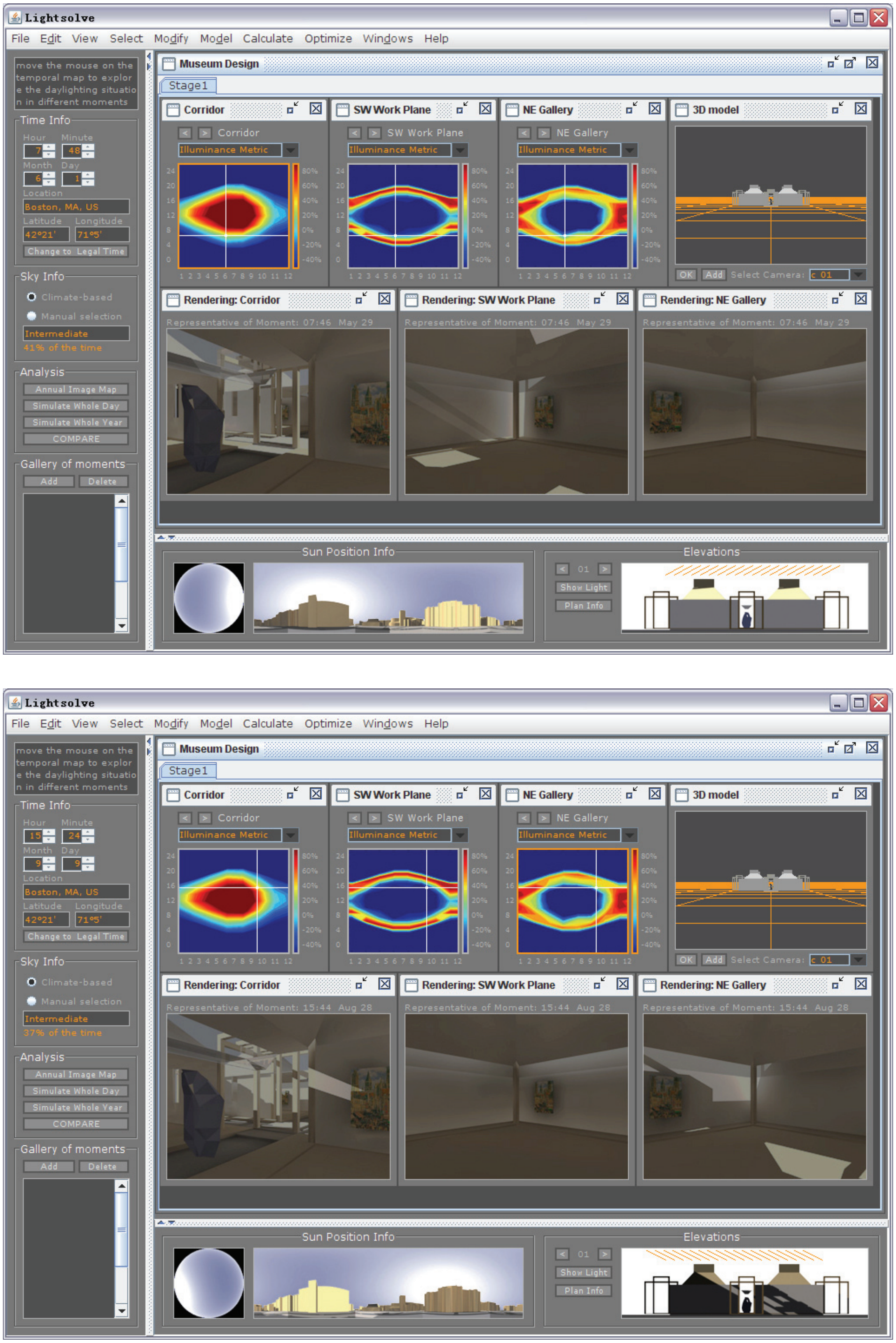


figure 5.36: Moments that the sky condition is intermediate. Just OK for corridor, but bad for SW work planes and NE walls.

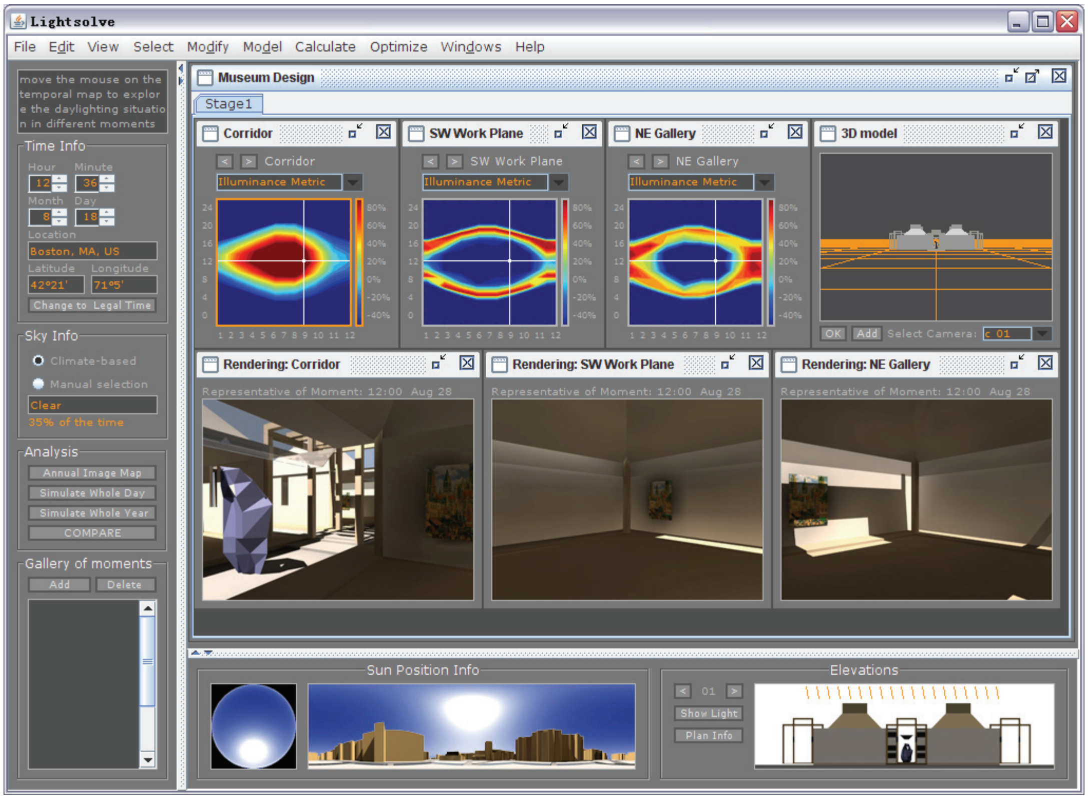


figure 5.37: Moments that the sky condition is most likely clear. Good for corridor, but bad for SW work planes and NE walls.

For the first AOI, the open corridor, what appeared as a bad moment on the temporal map corresponded to a rendering where no direct sunlight hit on the sculpture. Furthermore, the dominant sky condition on the platform was mostly overcast for those moments (figure 5.35). For the yellow and orange area on the temporal map (figure 5.36), which represents marginally acceptable performance, the rendering often shows that the sunlight patches are close to the corridor (figure 5.36). At the same time, the sun ray displayed in the elevation panel had a lower sun altitude comparing to those good moments in the central area on the temporal maps (figure 5.36); the sky condition for these moments are usually intermediate and clear-turbid sky (figure 5.36), which has less intensive direct radiation comparing to the clear sky. From around 9am to 3pm from February to October, the corridor had relatively good performance on the temporal map, and it also showed from corresponding renderings that there is plenty of direct sunlight coming through the skylight and hitting on the sculpture (figure 5.37), and the sun altitude in this period are in a high angle range (figure 5.37). The dominant sky type for these moments was the clear and clear-turbid sky (figure 5.37).

The second AOI and third AOI, the exhibition plane and NE walls had an entirely different situation. Both of them had good performance early in the morning and late in the afternoon (figure 5.35). The author also could not find any direct sunlight penetration on the corresponding renderings for this period (figure 5.35). Meanwhile, the sky info panel and the sun position info panel indicated that in most of the time, the overcast sky is the dominant sky type. When the cursor moves to the blue areas in these two AOIs' temporal maps, the dominant sky condition changed to be clear and clear-turbid in most of the time, and their renderings showed a lot of direct sunlight patches inside the space coming from the side and central skylight (figure 5.36-5.37). It showed the lighting level is not in the acceptable lux range for the exhibition of artwork, and is probably much higher than the maximum level because of the direct radiation from sunlight. The penetrated sunlight was probably the main reason causing this problem.

From this observation, it seems that for the open corridor, the problematic period in the winter (figure 5.38) was caused by weather variation in the Boston area. But for periods where performance was just acceptable (figure 5.34), it was because the sunlight has lower sun altitude (figure 5.38) and so that the light coming through the skylight could not directly hitting on the sculpture underneath, and the light supposed to be able to reach the sculpture was blocked by the ceiling near the skylight. The other two AOIs, the exhibition planes and NE walls, had good performance when the sky is overcast early in the morning, late in the afternoon, and in the winter. However, their performance dropped dramatically when the sky became clear and the sun angle became higher, because the sunlight went through the side and central skylight to hit on the plane and walls to bring extremely high illuminance level (figure 5.38). In this case, this initial design did not in fact reach its design goal (table 5.2, figure 5.32) and had to be revised in order to improve the current situation.

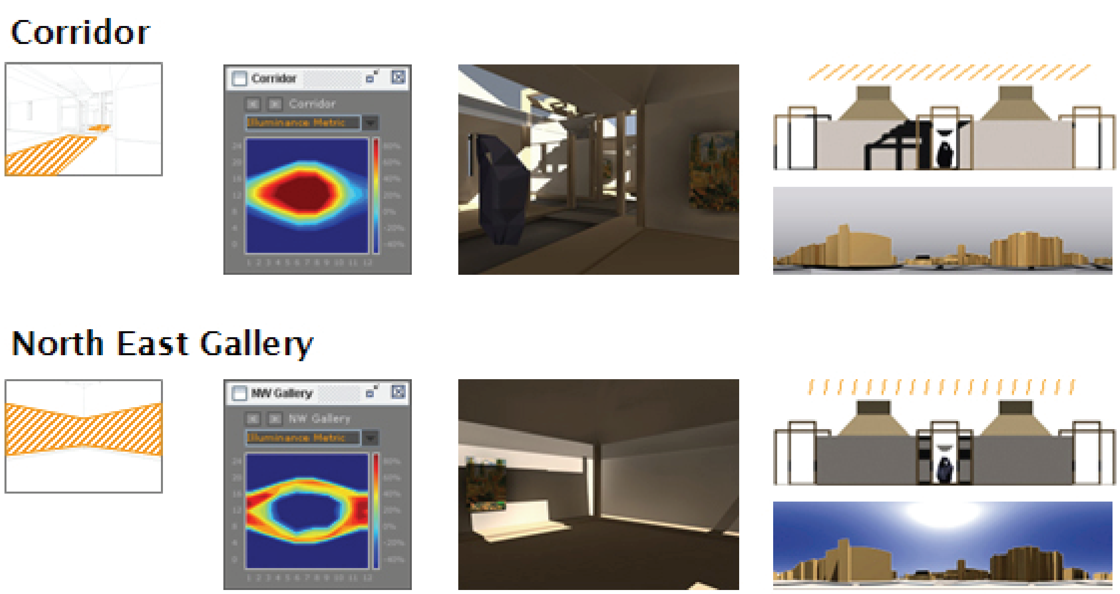


figure 5.38: Daylighting performances and their outside lighting conditions

5.2.2 Design Improvement and Daylighting Analysis

Design Modification:

The LightSolve program will include the optimization function to optimize the design based on the analysis and designer's initial goals in the future. The optimization engine is currently under development, so in this section, the design optimization process was done by the author based on her personal daylighting knowledge.

The frequently overcast sky in Boston, which caused the bad wintertime performance of the design, was clearly out of control of the author. However, it is possible to modify the corridor's skylight so as to allow the blocked sunlight through during the marginally acceptable moments (figure 5.35-5.37). Informed by the sun rays displayed in the elevation panel (figure 5.35-5.37), the author found out that the narrow skylight opening of the corridor could not allow low angle sunlight to come in and hit on the sculpture; therefore, increasing the width of the skylight may improve this situation. The author decided not to change the basic geometry of the skylight because she was satisfied with the proportion; instead, the opaque ceiling was displaced by a wooden railing structure with transparent glazing (figure 5.39-5.41). In addition, two reflective panels (figure 5.40-5.41) were added at the middle of the skylight so as to redirect some low angle sunlight to the sculpture.

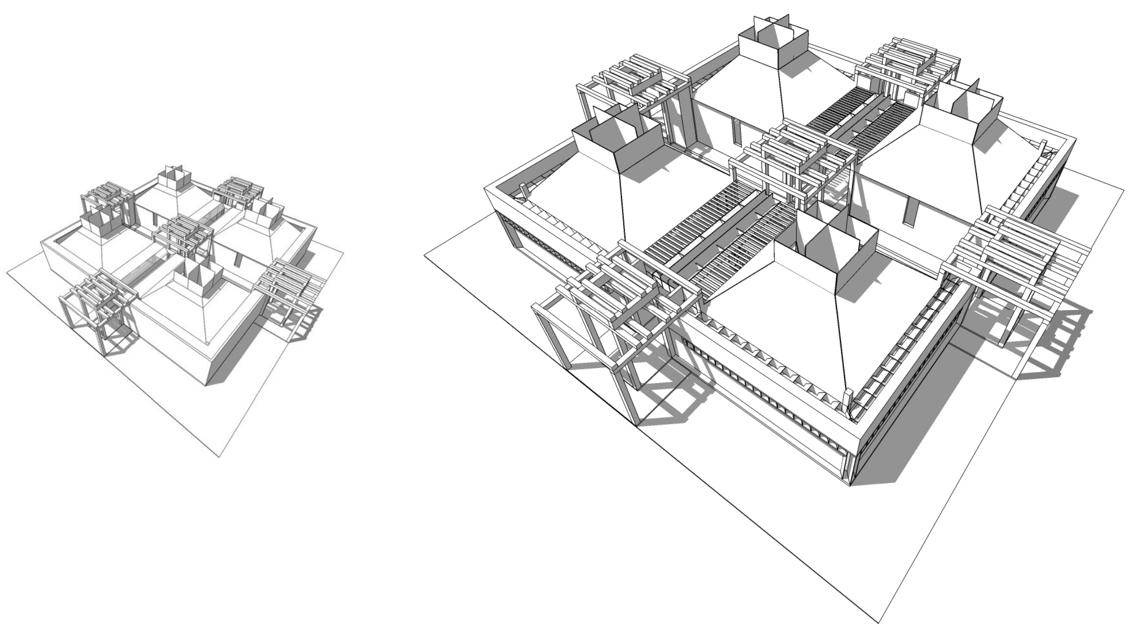
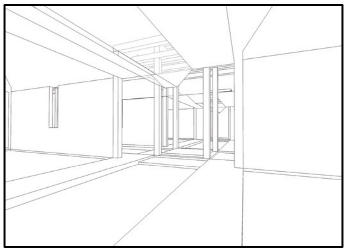


figure 5.39: Design adjustment from the initial design (left) to the second iteration (right).



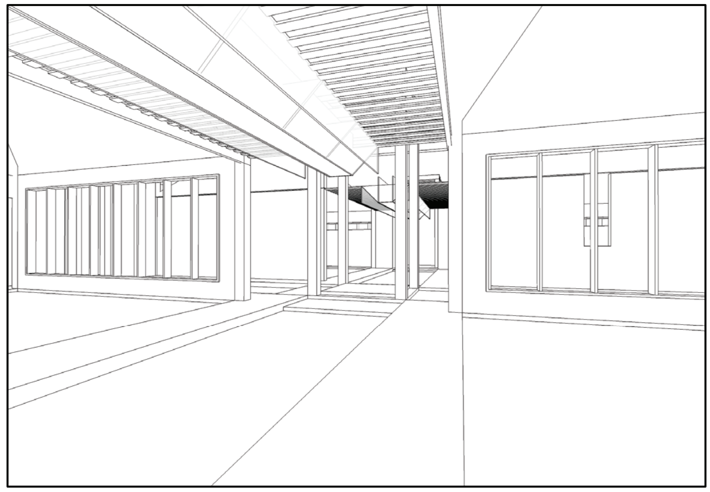


figure 5.40: Corridor adjustment:
initial corridor design (left)
new corridor design (right)

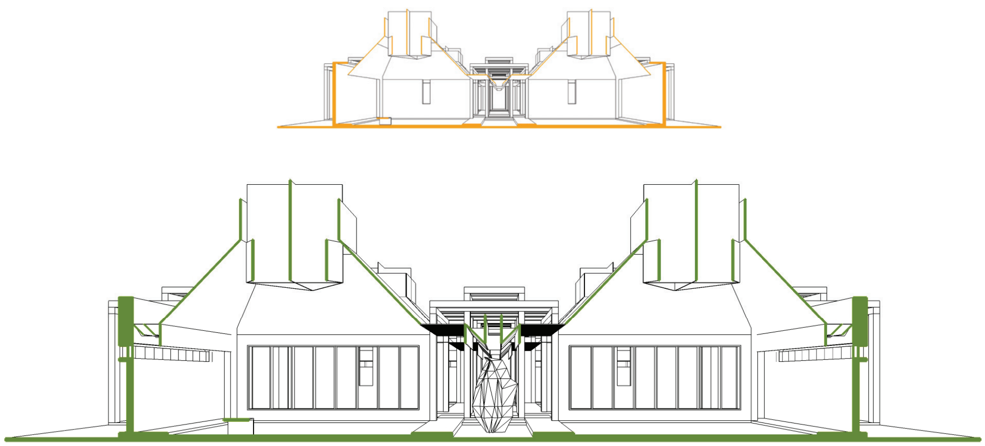
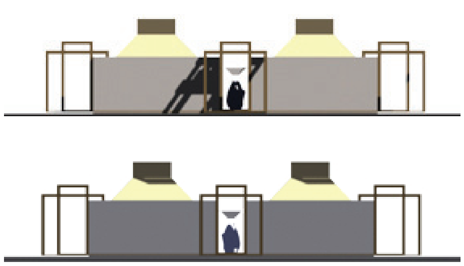


figure 5.41: Initial section (orange) and section in the second design iteration (green).



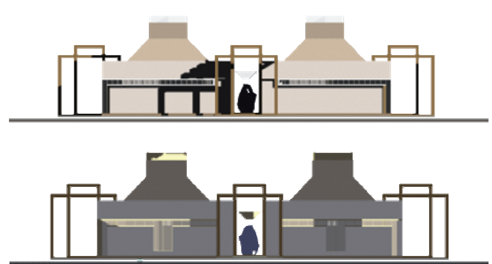


figure 5.42: Elevation adjustments: Original elevation (left), new elevation design (right)

For the exhibition planes and the NE walls, the failure to block sunlight from the side and central skylight was the cause of the bad performance (figure 5.36-5.37). In order to improve this situation, the author decided to design a louver system for the side skylight and add more panels for the central skylight (figure 5.41).

In terms of the aesthetic consideration, the corridor skylight in the initial design was a simple shape made by transparent glass (figure 5.39-5.41). The author refined its shape and added more detail for the supporting skeleton (figure 5.39-5.41) so as to bring a more elegant view of the skylight. From the renderings displayed on the platform, the author also realized that inner courtyards between the South and North gallery rooms had been totally blocked by solid walls facing the them (figure 5.41), and the narrow openings on these walls (figure 5.41) could hardly provide any interesting views of the courtyards for people inside. In order to exploit the view from the courtyards, the author decided to change those openings to big windows on north facing walls (figure 5.41). The north facing window would have no direct sunlight control issues, since it mostly had only diffused skylight in this particular location. Furthermore, informed by the renderings in the elevation panel on the platform, it seemed each elevation had little difference among others (figure 5.42), and it made the exterior view rather uninteresting. The author decided to add different openings for the South and North facing walls with horizontal and vertical louvers (figure 5.42) which were designed based on the possible sun angles displayed in the elevation panel.

The second version of the museum was constructed in SketchUp. The author kept the same design goals (table 5.2) and ran the daylighting evaluation using LightSolve algorithm as in the initial design stage.

Analysis Results for the Second Design Stage:

The temporal maps in the second evaluation showed the corridor better achieved its design goal compared to the first version (figure 5.43-5.44). Moments which had barely acceptable performance before showed improved performance in the current design. Comparing renderings in the comparison panel (figure 5.45), the corresponding renderings of the corridor showed that the new skylight system could bring much more sunlight for the sculpture (figure 5.45) for moments which only got little in the previous design (figure 5.45). The wooden railing structure also brought elegant shadow effects, and it helped to create a much stronger visual effect of the sculpture (figure 5.45). The open corridor could almost have access to the direct sunlight for most of the time when the sky is not overcast. The author felt satisfied with this part in this case.

The exhibition plane had improved performance compared to the first version, and NE walls had more good moments (figure 5.44), although its bad period increased at the same time. From the interactive browsing and the annual image map (figure 5.47), it seemed that the space of the exhibition plane still got some direct sunlight patches from the side and central skylight during its bad period shown on the temporal maps (figure 5.47). The same situation happened in the NE walls. The louver system still did not prevent some direct light from hitting on the walls (figure 5.48). In addition, when comparing renderings in the comparison panel, it showed that the revised corridor skylight brought much more sunlight on the walls when the sun angle became lower in the morning and in the afternoon (figure 5.45), which were moments that had acceptable performance in the previous design (figure 5.44). The renderings for both the exhibition plane and NE walls showed that panels of the central skylight did not efficiently minimize the sunlight penetration, and the louver system for the side skylight still needed to be adjusted in order to block all the possible louvers.

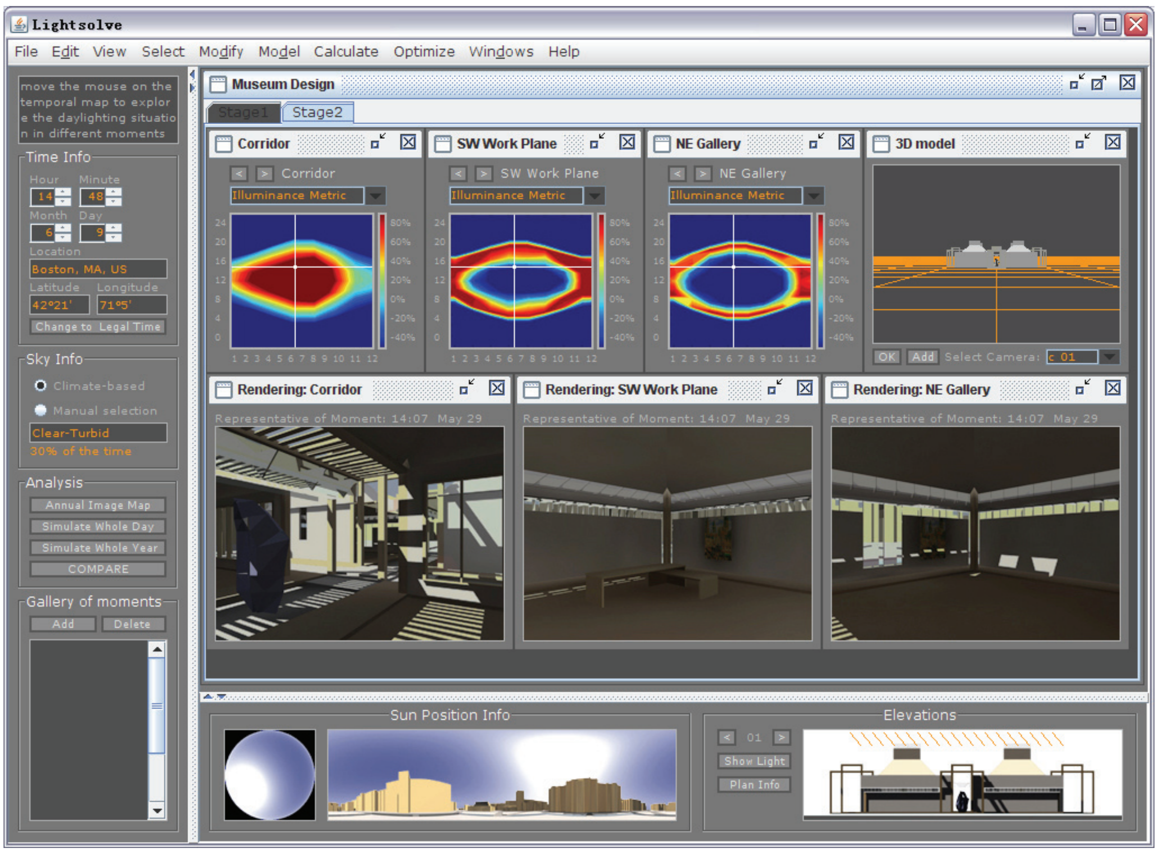


figure 5.43: Analysis result of the second design iteration

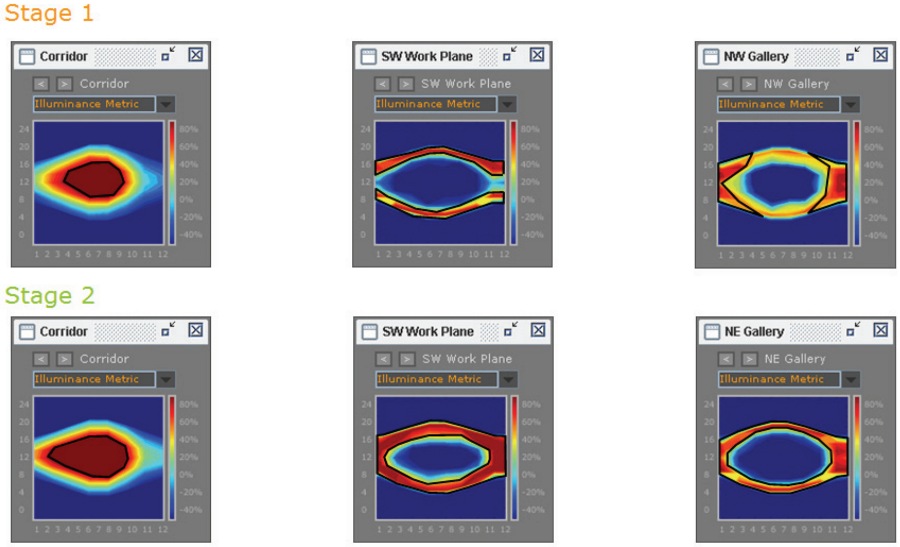


figure 5.44: Changing of the temporal maps

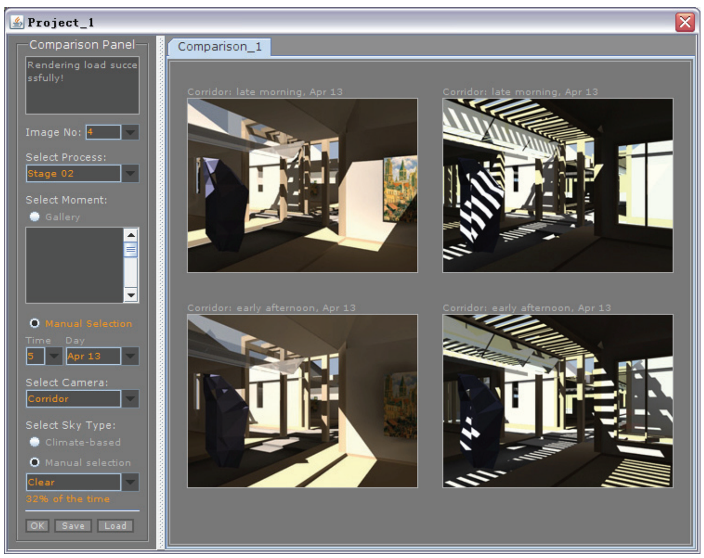


figure 5.45: Comparison of the corridor's performance.

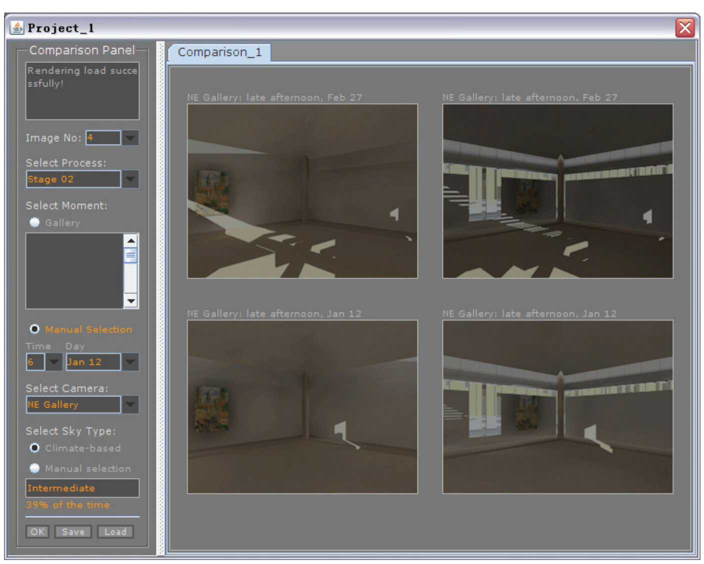


figure 5.46: Comparison of the NE walls' performance.

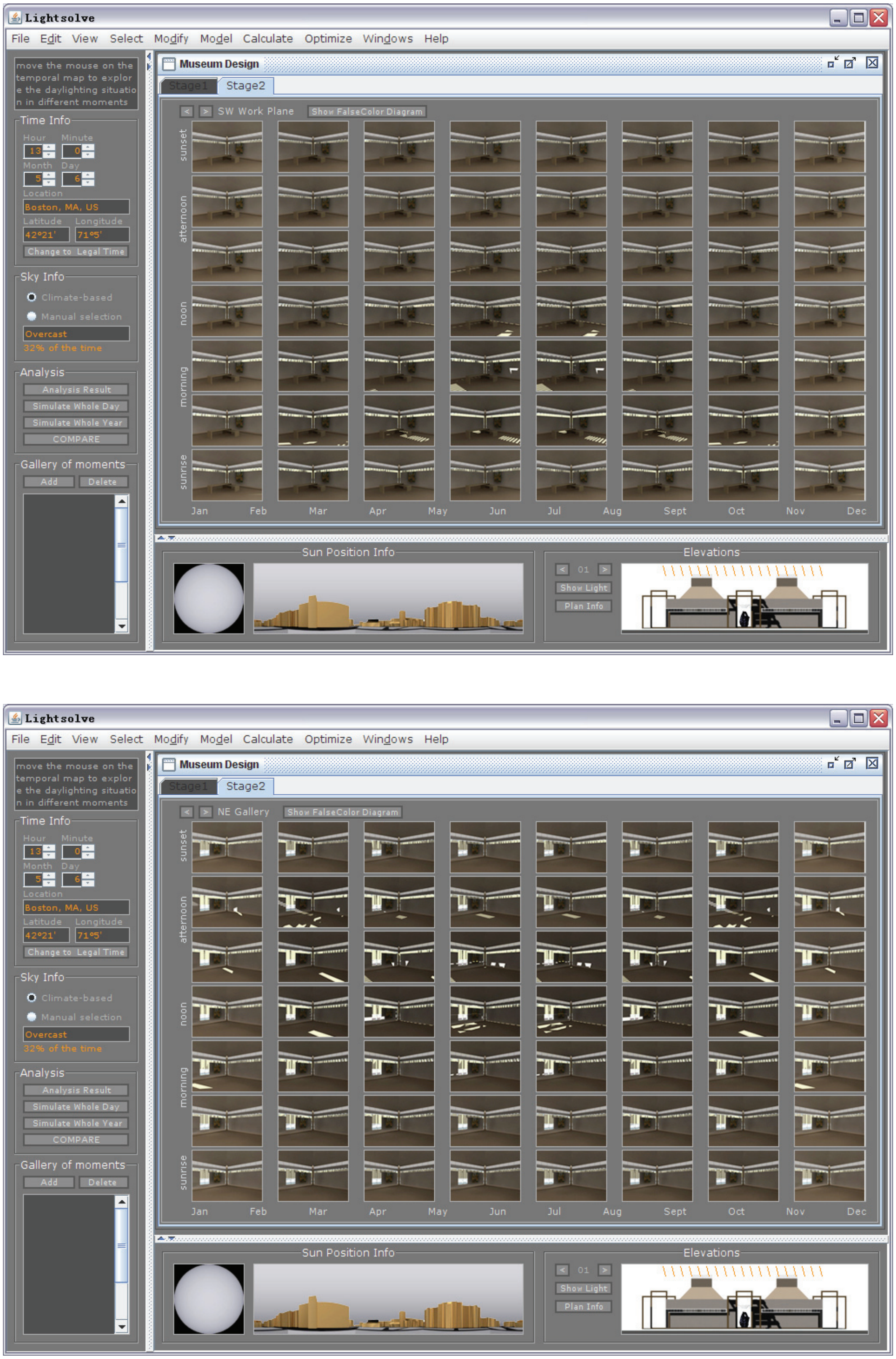


figure 5.47: Annual image maps for the SW work planes and NE walls.

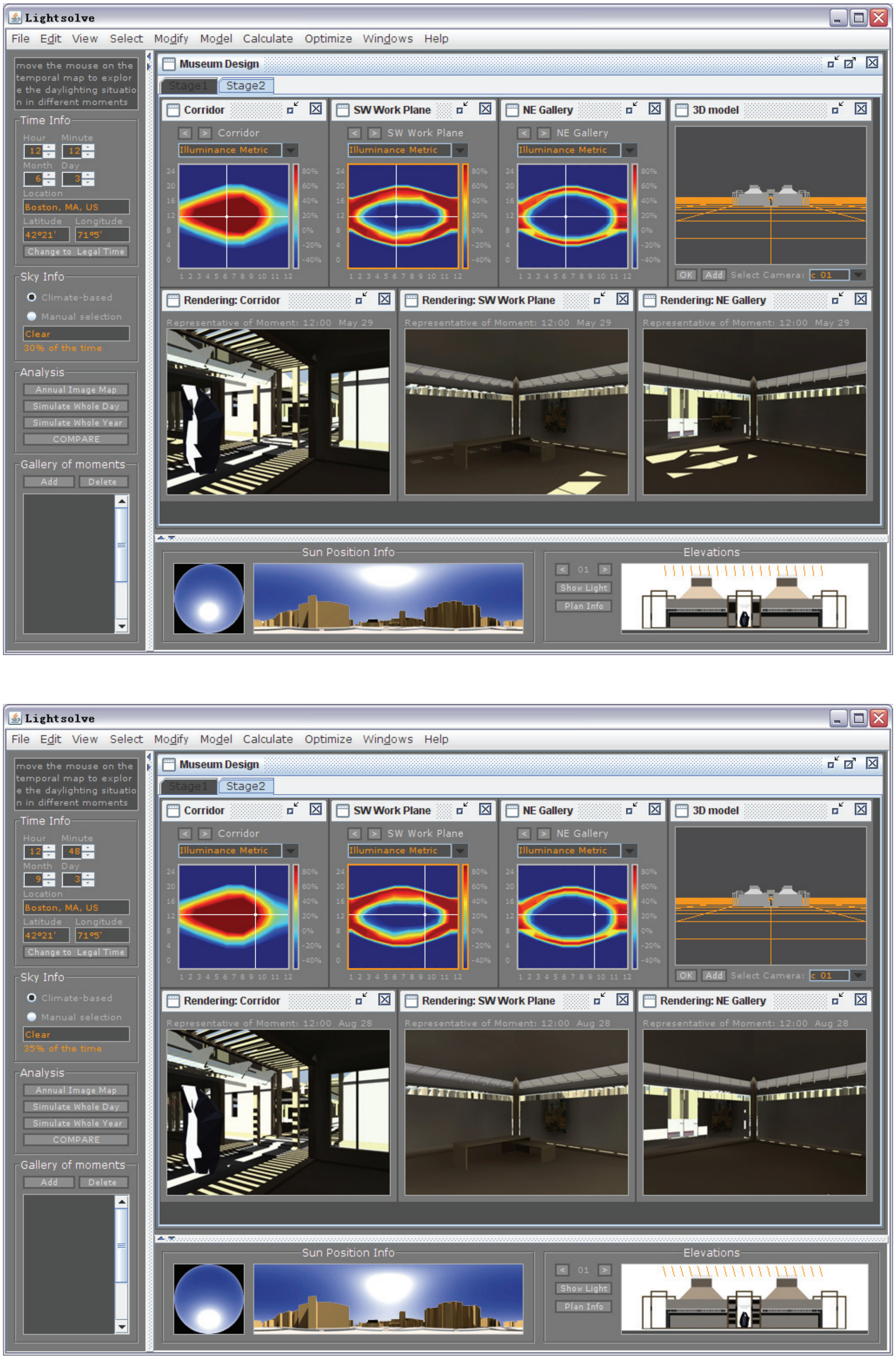


figure 5.48: Bad moments for SW work planes and NE walls.

5.2.3 Louver System Adjustment

Design Modification:

In the third design stage, the author decided not to make any modification of the open corridor area, because its performance almost achieved the author's design goal. This time, the author decided to strictly follow the sun angles displayed in the elevation panel on the platform to adjust the louver system for the side skylight so as to improve the performance of the exhibition plane and NE walls.

A "skylight sculpture" (figure 5.49-5.50) was designed to work together with the existing panels to prevent direct sunlight from coming through the central skylight. From exploring the analysis data from the second version, the author found that sunlight penetration happened when the sun angle is higher than a certain degree (figure 5.48). Using this information, both the vertical and horizontal louvers were used in this "skylight sculpture" (figure 5.49-5.50) to block the high angle sunlight from the very top and the lower angle sunlight from the side way.

Since the sunlight coming from the corridor brought more bad moments for NE walls (figure 5.46), the author decide to add some translucent curtains between the corridor and the gallery rooms (figure 5.51) so that the direct sunlight would change into diffused light with much less intensity.

A new digital model was constructed in SketchUp. Keeping the same design goals, the author ran another daylighting analysis based on the LightSolve's algorithm to check whether the third version could have any performance improvement.

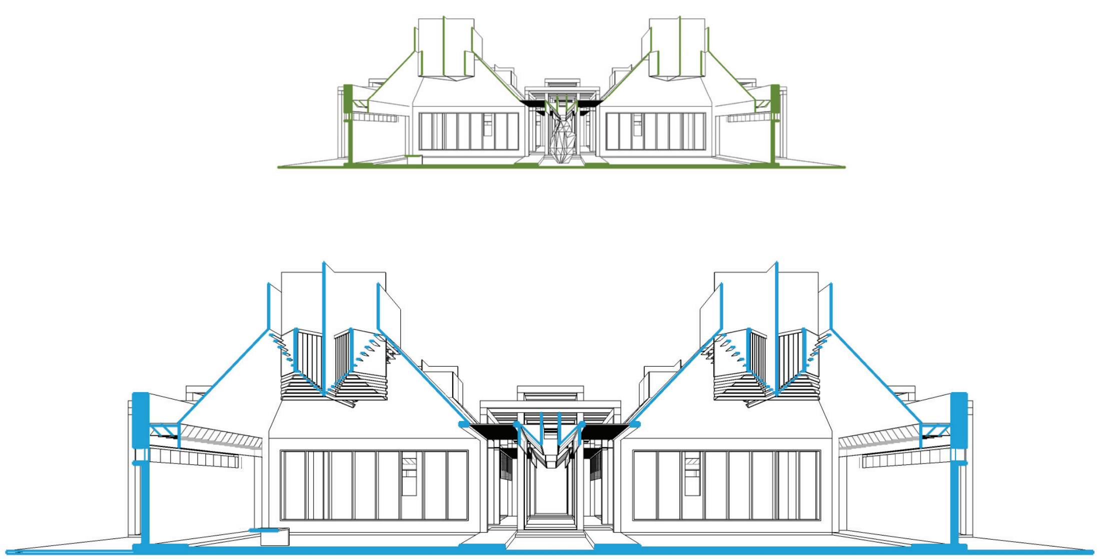


figure 5.49: "Skylight sculpture" added in the third design iteration (blue)

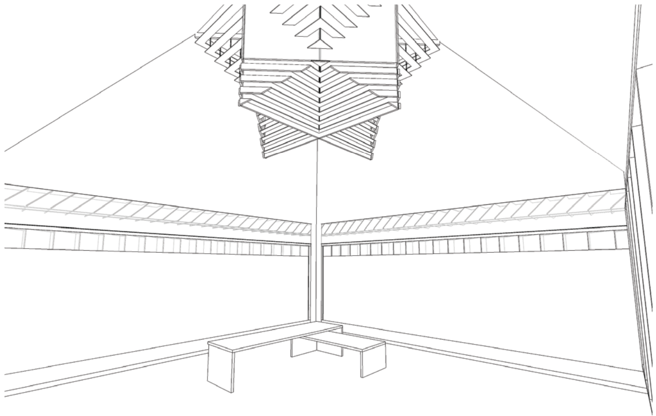


figure 5.50: “Skylight sculpture”.

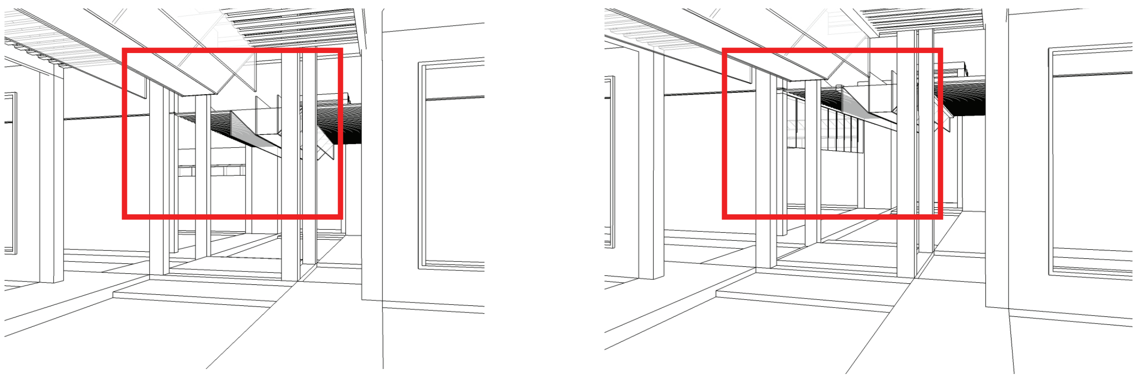


figure 5.51: Curtains are added to block sunlight from the corridor.

Analysis Results for the Third Design Stage:

The temporal maps showed a great improvement of the exhibition plane and NE walls (figure 5.52-5.53). Browsing those good moments on the temporal map, the rendering showed that the direct sunlight had been blocked satisfactorily (figure 5.52). During the period when the NE walls had been hit by the direct sunlight coming from the corridor skylight in the previous version, the sunlight no longer directly hit the walls in the current design (figure 5.54) because of the translucent curtains added (figure 5.51), and the performance of this period improved to “good”.

The bad periods of the exhibition plane and NE walls were similar, from around 10am to 2pm, May to August (figure 5.53, 5.55). From the renderings, the author found out that although the “skylight sculpture” diminished the sunlight patches (figure 5.55) it still did not prevent all the patches on tested areas from the central skylight during this period. In addition, at around 10am in this period, the louver system of the side skylight still allowed the sunlight to come through and hit the floor area close to the exhibition plane and NE walls (figure 5.55). Although the failure of blocking all the sunlight coming from the central and side skylight still caused the bad periods on the temporal maps in this design stage, the analysis results told the author that the overall performance improved a lot in the third version (figure 5.56).

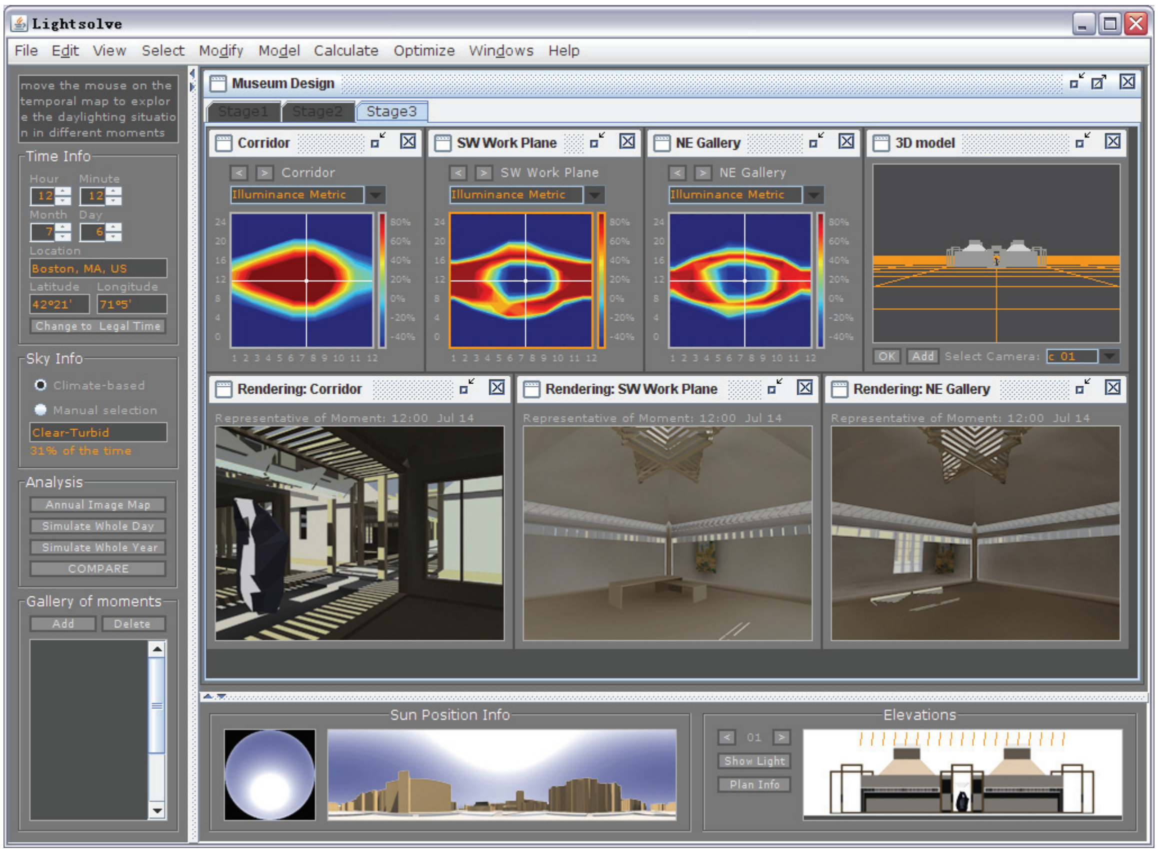


figure 5.52: Analysis result for the third design iteration

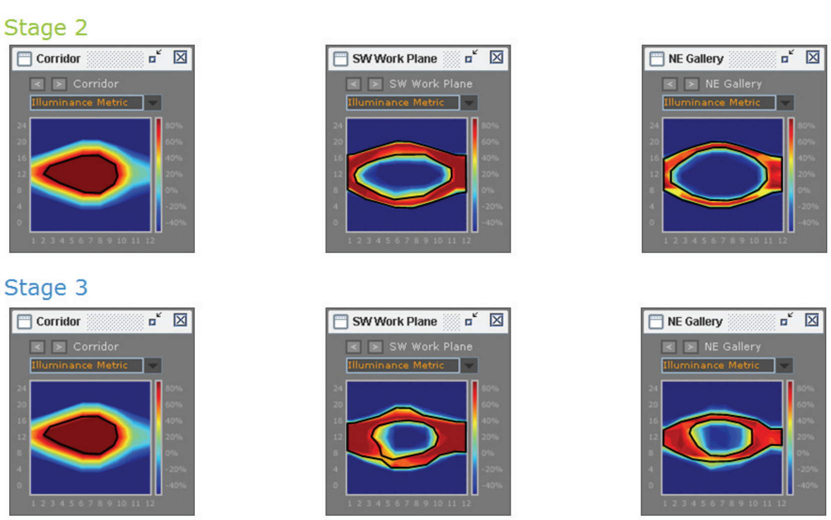


figure 5.53: Temporal maps' improvement.

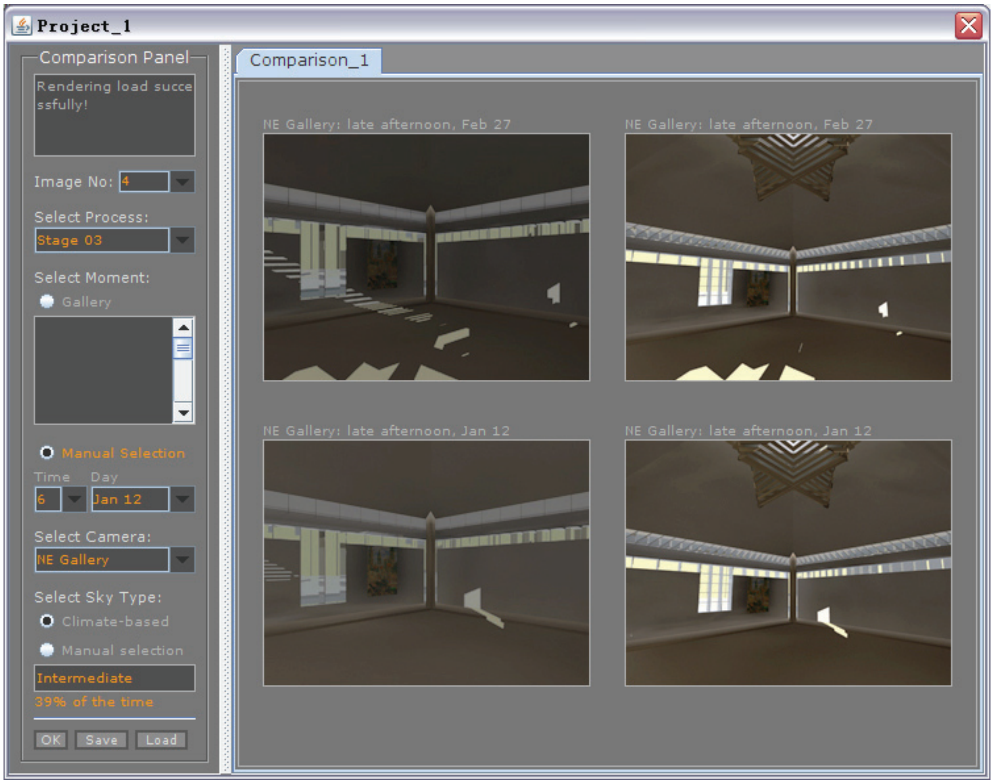


figure 5.54: NE wall's performance comparison between the second iteration and the third iteration.

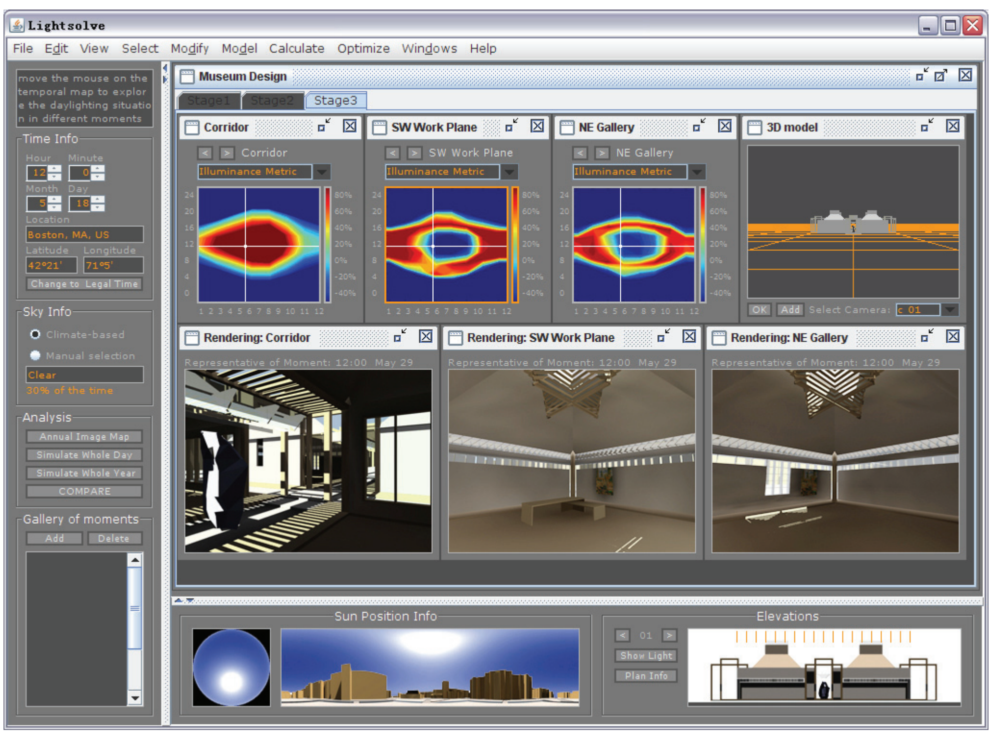


figure 5.55: Bad moments SE work plane and NE walls.

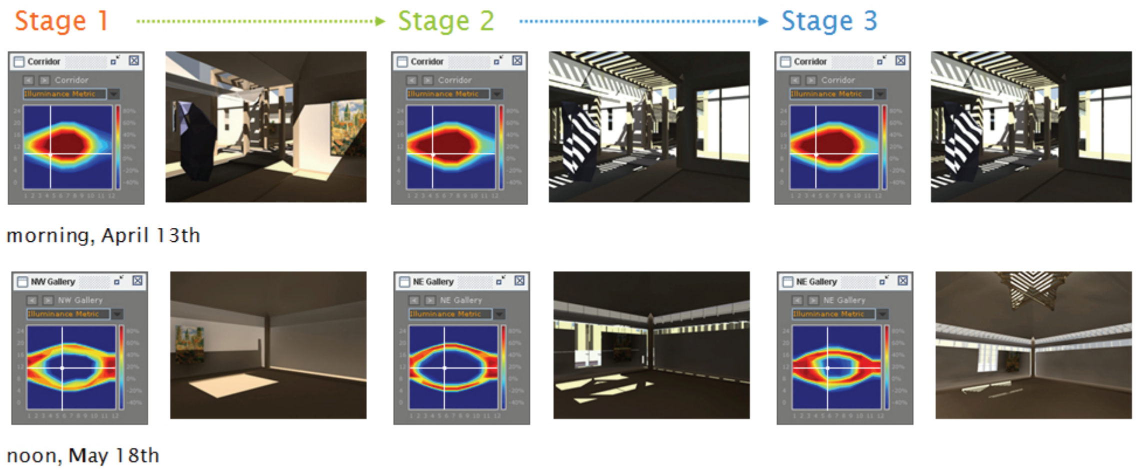


figure 5.56: Design improvement during the whole design process.

5.2.4 Demo Design Discussion

Three AOIs were selected in this demo museum design, and each of them had quite different design goals (table 5.2), but the platform could still easily allow the author to access any of them without jumping between several windows or gathering information for all of them manually for analysis (figure 5.55) as in most existing tools. It greatly shortened the time needed and made the design evaluation process much smoother. Even if the designer would like to check more than three AOIs at a time, which is usually what happens in real situations, he would be able to quickly browse any AOI using the “Back” and “Forward” function on the temporal map pane (figure 5.55).

The interactive browsing in the proposed data visualization platform provided the author a very convenient way to check daylighting performance over time from both technical and aesthetic aspects while remaining aware of the environmental impact on performance. The author spent no effort on viewing data for different moments, while in the case study of the existing tools in the first validation test, the author had to manually save all the information and organize them by time to make it easy for future review.

In this museum design, knowing the daylighting performance from both quantitative and qualitative perspective over the whole year is very crucial, since the design should achieve appropriate lighting level annually for the exhibits while providing a harmony visual effect that fits the artistic atmosphere. The interactive browsing in the platform gave the author a great freedom to do this without being interrupted by any complex manipulation process as in other existing tools. Being informed by these data simultaneously over the entire year enhanced the author’s understanding of the annual performance of this museum design and helped avoid the overlooking of some crucial moments.

More importantly, the information of the sky, surrounding, and sun ray position provided by the platform highlighted the importance of the environmental impact on the interior daylighting performance. The probability of each sky type reminded the author to have an emphasis on the dominant weather while still considering the influence of all other possible weather types. The sun rays displayed in the elevation panel assisted the author when redesigning the louver system for the side skylights. All of the information gave the author the chance to consider the environmental influence on the space performance and make the design more sustainable by truly adapting to the outside environment.

The comparison panel (figure 5.54) assisted the author in keeping track of the whole design process. The author could quickly compare renderings for any AOIs and check if the modified geometry and the louver system can truly improve the performance for the saved crucial moments or any other moment. The freedom to customize all related parameters (design stage, time information, AOI id, and sky condition) greatly simplified the ordinary comparison process in which the user has to save and organize the data himself.

In sum, the proposed data visualization platform created an efficient data transmission between LightSolve and the author. It informed the designer how the space interacted with light over the year while allowing her to keep in mind what circumstance formed this kind of lighting condition. At the same time, it minimized the designer's effort in gathering and viewing different types of data for several areas of interests so that the author could put most effort on analyzing the data and searching possible solutions to improve the design's performance.

5.3 Validation of Revealing Real Performance Issues

In order to test whether the proposed data visualization platform is able to reveal the real lighting situation of the space, the author interviewed Marsette Vona, the space user in Stata Center Room 32-376, to see what the actual lighting environment. The author then compared the information gathered from the space user with the information presented in the proposed platform.

The first thing Marty mentioned was that the space has no curtain or blind. It makes the space totally exposed to the natural light all the time. When it is in the morning and the sky is clear enough (figure 5.57), Marty said there are some strong glare issues. At his position, which is actually the area simulated in the case study in the first validation (figure 5.9), the computer screen becomes too hard for people to look at (figure 5.58), because plenty of sunlight is hitting on it. Although Marty described himself as a person who likes this kind of bright environment, he admitted this situation is in fact difficult for people to use the computer.

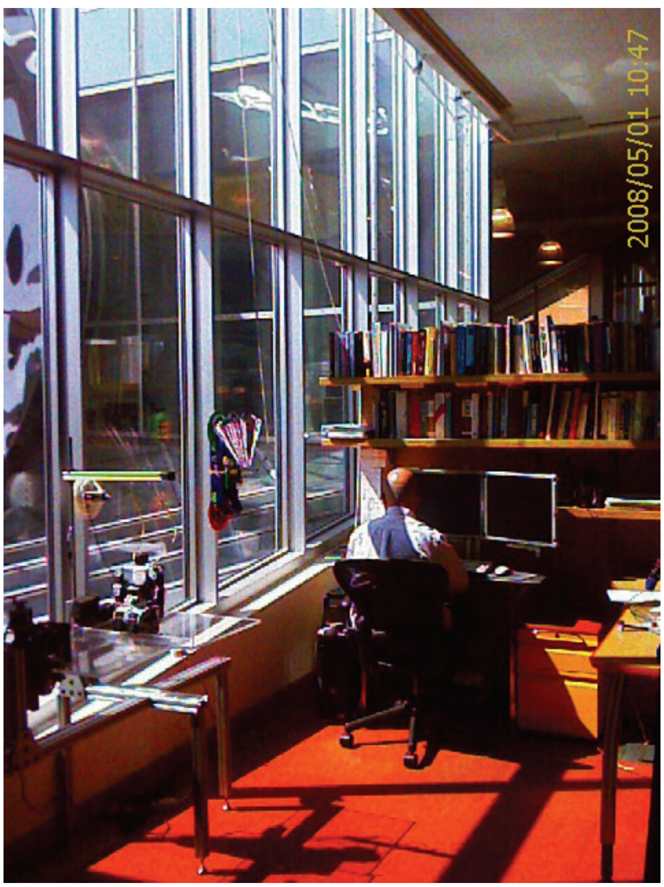


figure 5.57: Stata Center room 32-376 and its user Marty Vona.

figure 5.58: It is hard to look at the screen.

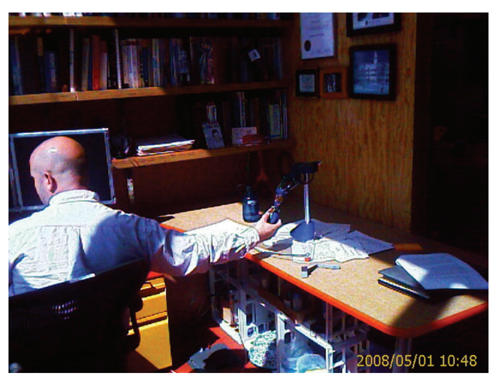


figure 5.59: Plenty of sunlight for working on robots.

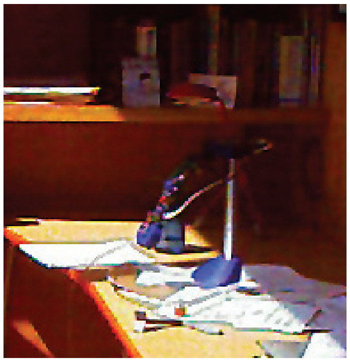
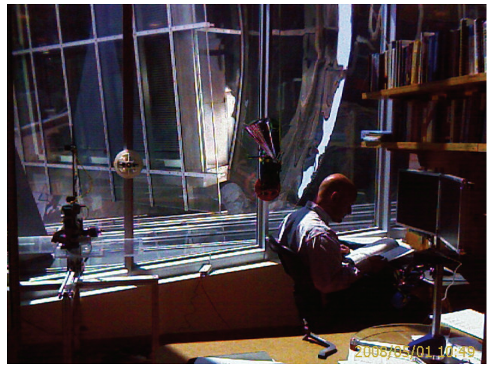



figure 5.60: Additional task lighting (left) and reflective exterior (right).

Besides working on the computer, a lot of Marty's job is to work on robots, which is actually a precise task that usually requires a pretty high illuminance level. Marty's desk for this work is perpendicular to his computer desk (figure 5.59). When the direct sunlight is coming in his working area and causing the serious glare problem on the computer screen, He felt very comfortable to work on his robots because the sunlight brought him a very bright environment. However, the period he can get the direct sunlight at his position is usually a couple of hours in the morning. When the sunlight no longer has the access to this space, the lighting level drops down dramatically, and Marty has to add additional task lighting (figure 5.60) to maintain enough light for his robot work. The same situation happens when the sky is cloudy.

Sometimes when the sky is partially cloudy, then the interior lighting environment changes quickly between bright and dim. Marty thought it makes people's eyes feel difficult to adapt the lighting environment in the same speed. Although the exterior building is covered by the highly reflective metal surface (like mirror, figure 5.60), he said it does not really bring him any reflected sunlight. However, the people sitting opposite to his desk complained she is actually bothered a lot by the reflected light during the afternoon.

From Marty's information, it is apparent that the space has very high illuminance level when the direct sunlight is coming, but it has a serious glare problem on the computer screen at that moment. When there is no direct sunlight or the sky is overcast, the space appears too dim to perform precise task. The direct sunlight usually comes in during the morning for couple of hours. The exterior reflective surrounding does not bring him much reflected light.

Based on this information, the author ran an analysis in LightSolve (the temporal map and renderings were all pre-computed in Radiance). For the illuminance temporal map, the author tested the area of the working plane using the same digital model used in the case study of existing tools in Chapter 5.1 (figure 5.9) with the goal of achieving lux level larger than 800lux, which is good for precise tasks. For the luminance temporal map that takes care of the visual contrast, the author tested the luminance ratio between the computer screen and the wooden board behind it (figure 5.58), and the goal is to have the ratio between 1 and 1:10, which is appropriate for ordinary people (figure 5.61).

From the analysis result displayed on the proposed platform, the illuminance temporal map (figure 5.62) quickly told the user the space reaches its goal well enough from around 8am to 12pm, mid March to October. During other period, the illuminance level on the working plane was out of the desired range. However, on the temporal map that represented the luminance ratio, the bad moment was actually similar with the good moment shown in the illuminance temporal map.

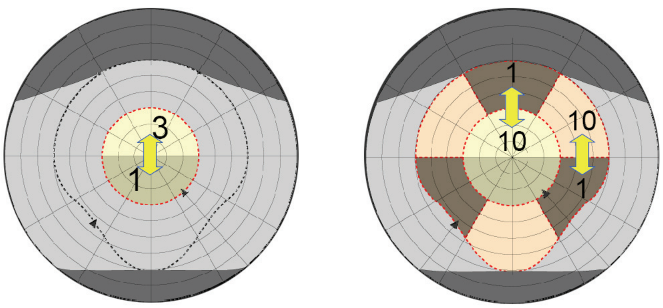


figure 5.61: acceptable illuminance ratio for human.

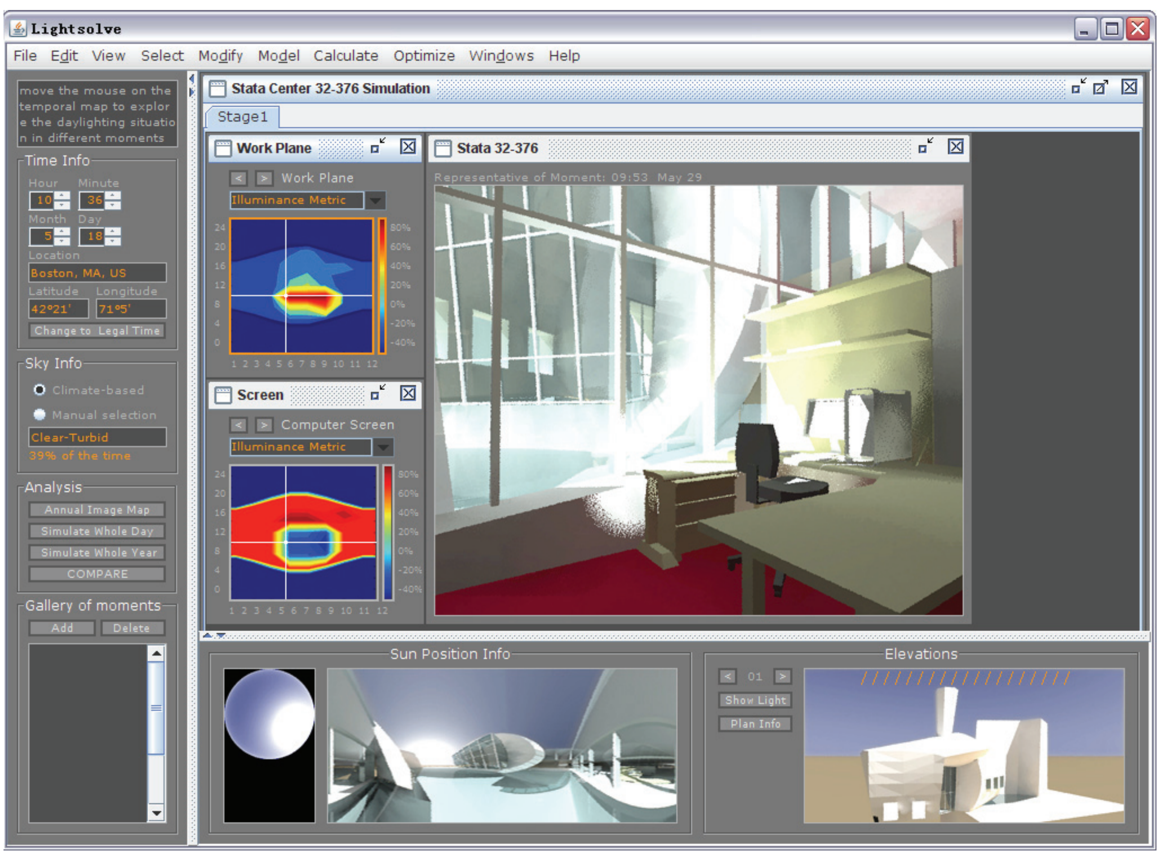


figure 5.62: Analysis in the proposed data visualization platform

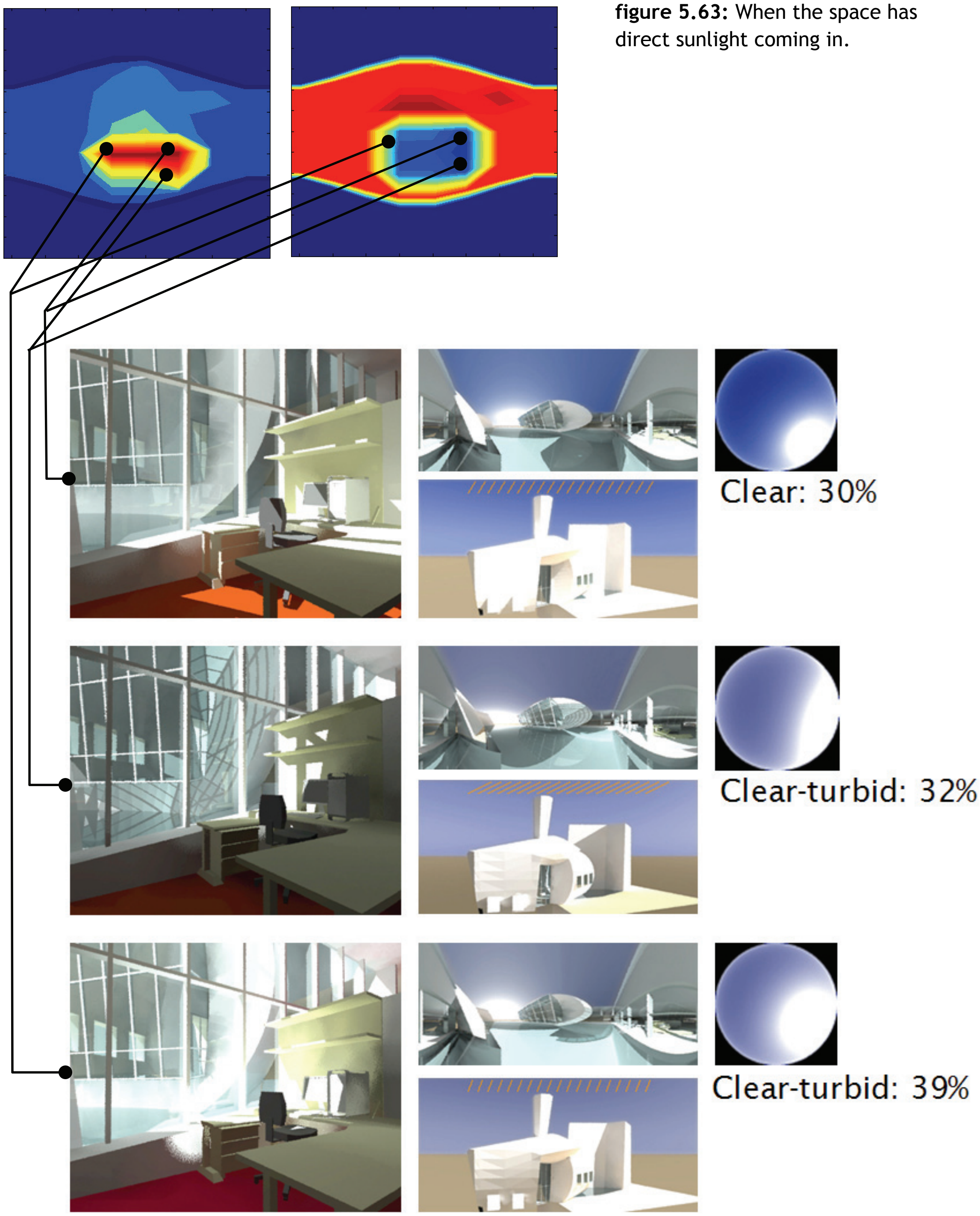
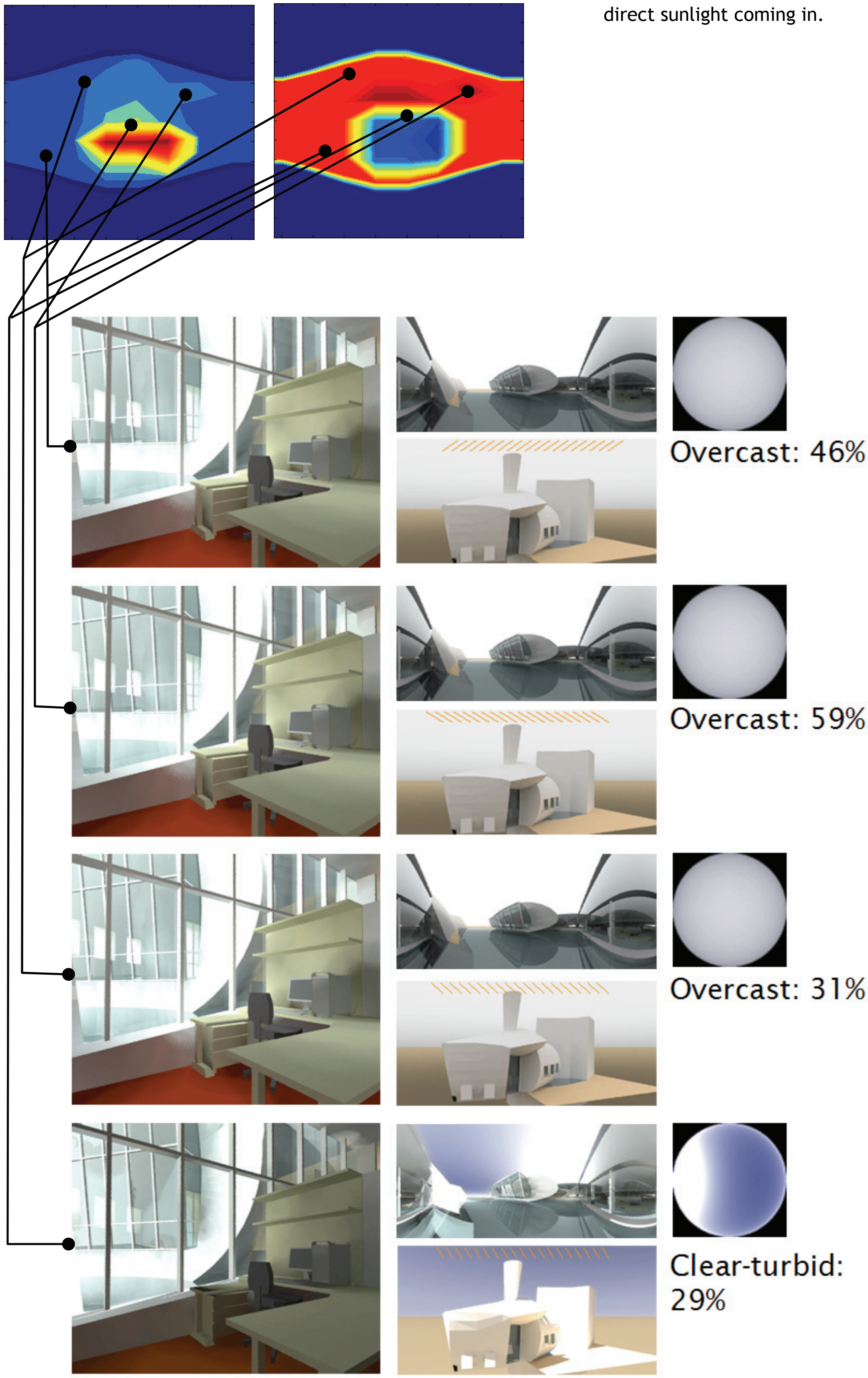


figure 5.63: When the space has direct sunlight coming in.

figure 5.64: When the space has **NO** direct sunlight coming in.



The author than browsed this period to view corresponding renderings of the space. It turned out that most of the time the working plane got the access to the direct sunlight, while the computer screen was also exposed to the direct sunlight as well (figure 5.63). This phenomenon explained why the illuminance temporal map considered that period as a good moment while the luminance map considered it as a bad moment. And this situation fitted the information from the space user.

When browsing those bad moments on the illuminance map, the author also found out that the dominant sky type was usually overcast in the sky info panel (figure 5.64). When the sky turned to other clearer sky condition (figure 5.64) during this bad period, the rendering always showed the work plane had no access to the direct sunlight (figure 5.64). This information matches what Marty introduced in the interview. He said the space becomes too dim for him to work on the robot when the sunlight moves away from his work plane and when the sky is cloudy.

In order to understand why the space interacts with the sunlight in this manner, the author checked the rendering change of the surrounding (figure 5.63) and sun rays displayed in the elevation (figure 5.63). It showed that during the good period on the illuminance temporal map, the sun altitude is usually not very high (figure 5.63). This makes it possible for the sunlight to penetrate into the space and reach the tested work plane. There are many other moments that have the similar sun altitude (figure 5.64), but from the rendering, it showed the work plane still was not hit by the sunlight (figure 5.64). By checking corresponding surrounding renderings (figure 5.64), the author realized the sun was blocked by exterior obstructions. By manually customizing sky type to clear, it showed there are some other moments that were supposed to have the direct sunlight access to the work plane; however, the dominant weather condition of them is overcast. Therefore, the illuminance and luminance temporal map did not give many credit of this direct radiation in their calculation. In the future, the user will be able to directly view the sun azimuth by switching elevation panel to plan panel so as to check the direct sunlight access more comprehensively. Currently, this function is till under developed and not yet ready to use in this thesis.

This validation test demonstrated the proposed platform has a strong ability of comprehensively presenting the real lighting performance of the space and its potential problems. The analysis results displayed in the platform greatly matched the information provided by Marty, the space user in the real place. Further more, the environmental information displayed on the platform, such as the sky type and its probability and sun rays in the elevation panel, efficiently helps the user to connect the daylighting performance with the outside lighting environment and understand better its influence over time. In consequence, the designer is able to get a comprehensive and realistic daylighting evaluation of the design, and he has better chance of making appropriate design improvement informed by the information delivered by this platform.

5.4 Validation Survey by Intended Users

The aim of this survey is to test whether the proposed data visualization platform for LightSolve helps the designer understand better the daylighting performance and potential problems over the year and be aware of the influence of the outside lighting condition. In this survey, first a forty minutes presentation was given to the architectural student. It introduced the concept of LightSolve, features of this platform, and the demo museum design supported by it. Then the student had a hand-on exercise on the platform to experience it in person. Finally, the student filled out a questionnaire (appendices 5) which aims to gather feedback about the LightSolve project and this data visualization platform working as an analysis interface for LightSolve. This survey was in an interactive way, and the student could ask questions and discuss with the author at any time during this survey.

Four architectural students from MIT Department of Architecture participated in this survey. Two of them are in the final semester of the Master of Architecture program; one of the other two students is the senior student of the Bachelor of Arts in Architecture major and has already been admitted by the Master of Architecture program at MIT, and the other one comes from the first year Master of Science in Architecture Studies in Computation and Design with a professional Bachelor of Architecture Degree already. All of these participants can be considered as having the professional experience in the architectural design.

5.4.1 Survey Result

1) The ordinary way to test the design's daylighting performance:

The questionnaire began with a question of identifying in what way the participant usually tests his design's daylighting performance. Only one student from M.Arch program selected "Daylighting analysis tool" for this purpose; all other students use either "physical model" or "computer rendering" or both (appendices 6). It indicated that architectural students are more likely to consider the daylighting performance from the aesthetic perspective than technical perspective.

2) The function of the information delivered by the temporal map on the platform:

All participants believed the temporal map could provide a comprehensive daylighting evaluation of the design (appendices 6). Most of them thought temporal maps works well on considering the time factor in the daylighting design. In terms of detecting potential problems, although all of them indicated they can quickly target the problematic period of the whole year by the assistance of temporal maps, some of them still thought they need extra step to figure out what the problem is by looking at other data displayed on the platform. Some of them thought the weather information embedded in the temporal map were not that straightforward to figure out, and they need to combine the sky information displayed on the platform so as to integrate the weather factor in their design.

These feedbacks clearly showed that the temporal map is able to provide an overall estimation of the space performance, however, the designer still need to receive more detailed information, such as renderings and sky type information in order to understand better the quantitative information they've got before.

3) The link between temporal maps and renderings:
All participants considered the dynamic link between temporal maps and renderings in the interactive browsing could help them identify the problem type quickly (appendices 6), since the rendering can directly show whether the space is too dim or bright, or it has too much direct sunlight patches. This result fits the feedback from the previous question that the user need more information to detect the potential problem after they informed by the temporal map.

Two participants thought this link helped them detecting what caused the daylighting problem, because they could figure it out from the rendering. However, the other two participants thought, although rendering and other information on the platform could assist them to figure out the reason, the process was still done by the user himself. Thus, they considered this dynamic link provided by the platform was not directly helpful for detecting what causes the problem.

4) The combined info of time/date and daylighting performance on the temporal map:
All participates' answers of this question are similar (appendices 6). They all believed that the temporal map can guide the user to browse renderings for GOOD and BAD moments and be used as an interactive time/date graph to browse renderings. It demonstrated that linking the quantitative temporal map with the qualitative rendering over time to create the interactive browsing assists the user to quickly target the crucial moment and easily access to data of any moment in a convenient way. As for connecting space performance over time with outside lighting conditions, most participants felt they still needed to look at other environmental information displayed on the platform to create such a connection.

5) Weather information displayed on the platform:
All participants agreed that the weather information displayed in the sky info panel, sky dome and surrounding view panel (appendices 6) was very useful for them to understand performance over the year as a result of sky type probabilities and to connecting the visual effect with different sky types. In terms of adapting the design based on the predominant weather condition, three participants gave less credit on it. They thought they needed to make a further synthesis of the weather variation and the daylighting performance themselves in order to let the design adapt to the local environment. As mentioned in the first question, most participants in this survey have little professional daylighting knowledge. They are used to evaluate and develop a design from an aesthetic perspective. It explains why most of them thought they need more effort to integrate the weather information displayed on the platform and make their design adapt to this weather variation.

6) The sun ray displayed on the elevation panel of the platform:

The author got similar answers of this question (appendices 6). All of them agreed that dynamically showing the sun ray changes on the elevation panel was an informative way to relate daylighting performance with sun angle variations. During the interview, all participants showed a great interest of this function, because they considered the sun angle as an important parameter in determining things such as the buildings geometry, openings, etc.

7) The influence of the quantitative data (temporal maps) and qualitative data (renderings) in the design process:

All participants thought the quantitative and qualitative data could give them more confidence in their design performance (appendices 6). However, most participants considered they still needed to synthesize themselves the information displayed on the platform in order to figure out the reason of the problems, the way to fix them, and explore alternatives which have not been considered based on their previous experience. These answers expressed that designers, who are used to evaluate the design simply from the aesthetic perspective, have a demand of having the software help detect potential problems of the daylighting performance and make design improvement. In fact, the platform itself works as an analysis interface in LightSolve, the LightSolve project will include the optimization function in the future that can assist the designer to make diagnostic of the existing problems and propose possible solutions based on the designer's initial design goals.

8) General feedback of the platform:

All participants felt that they had no difficulty in learning the platform quickly with their design background (appendices 6). And most participants thought the platform had an educational potential in terms of acquiring daylighting knowledge. As discussed in the previous question, they thought the LightSolve program should provide more assistance on detecting the reason of the problem and proposing possible solutions so as to meet all the needs of designers.

Question 11 and 12 are not discussed in this thesis, because they refer to the broader LightSolve project and have no direct relationship with the data visualization method developed in this thesis.

5.4.2 Survey Discussions

This survey indicated that the link between quantitative temporal maps and qualitative renderings over time helps the designer to comprehensively understand the annual daylighting performance based on the design goal from both technical and aesthetic aspects and find out the potential problems. In addition, the way of integrating information such as the sky condition and sun ray into the interactive browsing successfully emphasizes the influence of the outside lighting conditions in the interior lighting performance. More important, the platform allows the user to acquiring more daylighting knowledge during the design process, and it may increase the chance of integrating daylighting considerations into the designer's initial concept. In consequence, these responses showed that the proposed data visualization platform creates an efficient data transmission process between the platform and the user and support better the design process from a more integrated perspective.

Chapter 6

Conclusion

6.1 Thesis Achievements

This thesis proposed a new data visualization method to better inform and support the architectural design process in terms of daylighting, and developed a functional platform that implemented the proposed method.

In the background research, the author first studied the influence of daylight in architecture and did a background research of the architectural design process and looked at the data delivery and use during this process in general. From this study, the author found out the importance of having a smooth and efficient data visualization process is crucial to maintain a continual design process and comprehensive inform the design decision making. The author then analyzed the necessary data lighting representation in terms of daylighting design and in which way they should be presented and interpreted. In addition, the author also did research on the current lighting simulation tools to see what types of data representations they provide, how they visualize these data to the designer, and what their problems in term of data visualization are.

Based on those researches, the author developed a new data visualization method that intends to improve the current situation and developed a function data visualization platform. The author decided to use two the existing research work in the proposed method because their attributes fit the need of the method. The first one was the temporal map developed by PhD student Sian A Kleindienst. The second one is the render engine currently being developed by RPI Department of Computer Science. Since the render engine is yet not ready to use, all the renderings in this thesis were produced in 3Ds Max and Radiance.

In order to test the efficiency of the proposed method, the author did four validation tests. The first validation test made two case studies based on existing buildings (Yale center for British art and Stata Center Room 32-376) using 3Ds Max and Ecotect, two typical tools of existing lighting simulation tools. These case studies showed their capability of producing various data in high quality, however, it also showed they do not pay too much attention on how the data are visualized and delivered to the designer in order to better inform and support the design process. It showed that the proposed platform would keep the design process in a smoother way than these tools in the comparison at the end of the first validation.

The second validation test was performed to test how a design project can be influenced by the proposed data visualization method. A demo museum design was analyze in the proposed platform from its initial design stage, and most of the design improvement were greatly informed by the data presented on the platform. This validation test showed that the proposed method can assist the designer to understand better the daylighting performance over year and find out possible design solutions without interrupting the design process because of the data collecting and delivery.

The third validation tests focused on whether the proposed method can reveal the real performance issues. The author interviewed the current space user at Stata Center Room 32-376 to see what the problems of the space were. The author then built digital model and ran analysis in the proposed platform. It turned out the problems shown on the platform greatly matched the problems told by the space user.

The fourth validation was a survey to intended users. Architectural Student at MIT Department of Architecture participated into this survey. The questionnaire results showed that all of them thought the platform was very easy to learn as their designer background, and the dynamic links among different types of data helped them to comprehensively understand the performance.

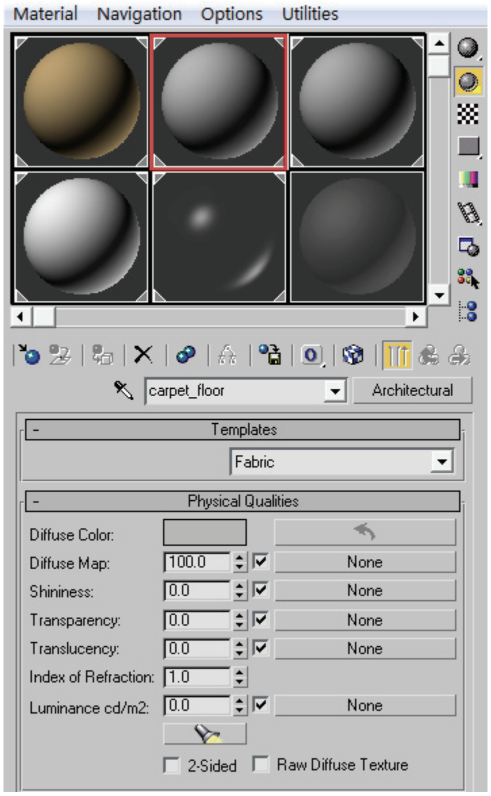
These validation tests showed the proposed data visualization method achieved its objective of helping the designer to understand better the design performance while minimizing the extra effort needed to get all the data and analyze them efficiently.

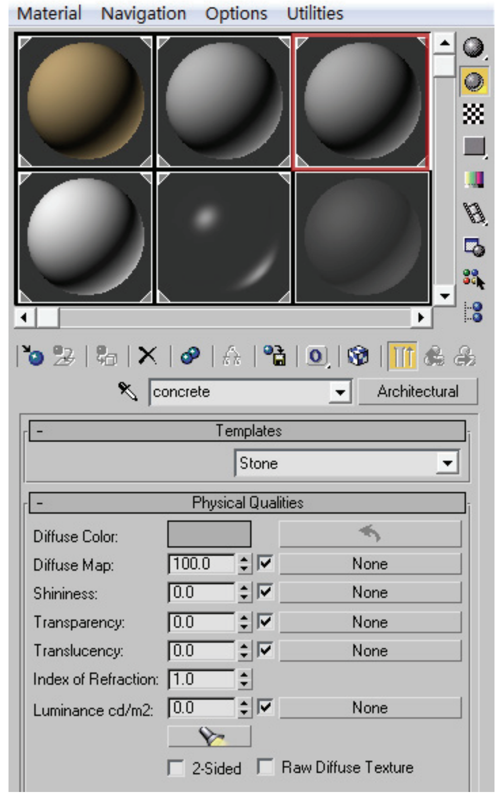
6.2 Future Work

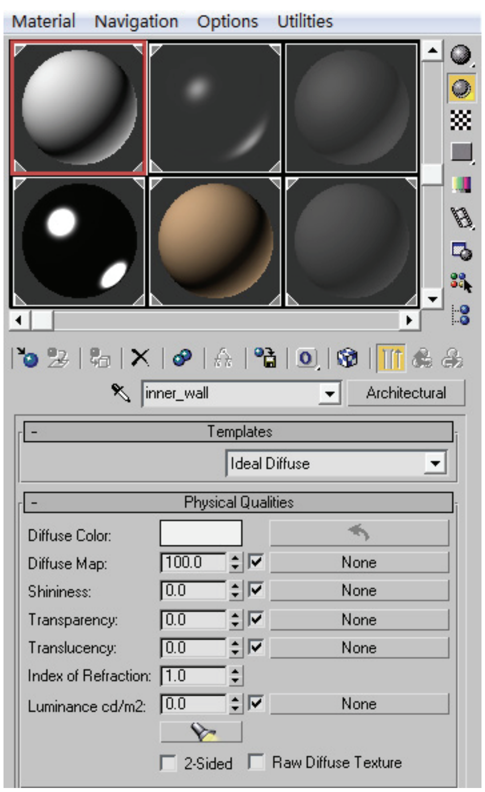
The data visualization platform will be integrated into the LightSolve project as an analysis interface in the future. It will be needed be linked with the render engine developed by RPI Department of Computer Science to make the proposed platform more functional.

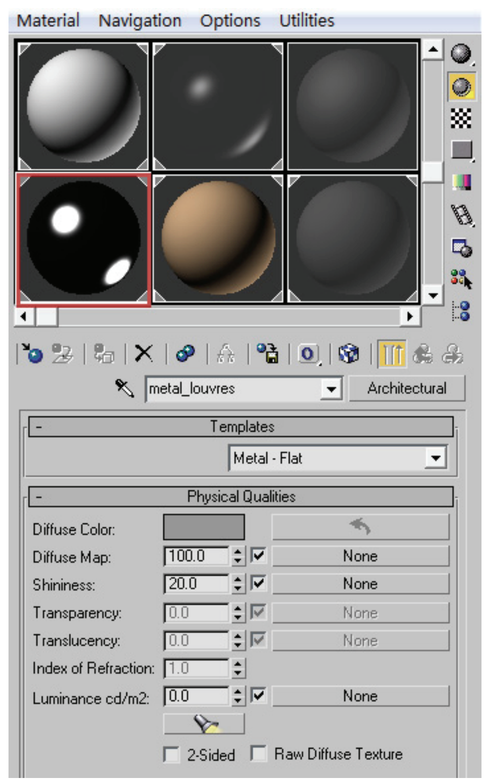
From the survey in the fourth validation test, it revealed that the designer needs to have an assistant to reveal reasons of those potential performance issues and provide possible design solutions. This fits the objective of the broader LightSolve project that aims at developing a highly innovative computational tool for daylighting design, which will be able to inform the design process through an interactive, goal-driven optimization based on expert rules of daylighting design in the future. The data visualization method proposed in this thesis can be extended to meet new data transmission demands during that optimization process.

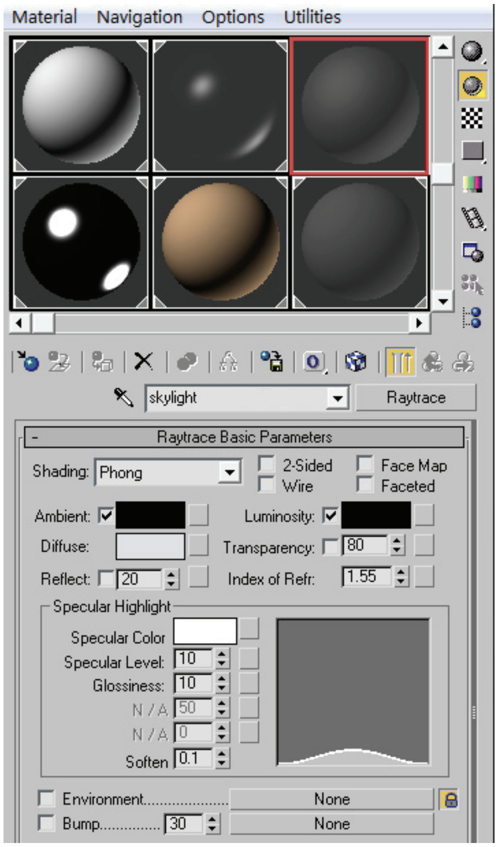
Appendices 1







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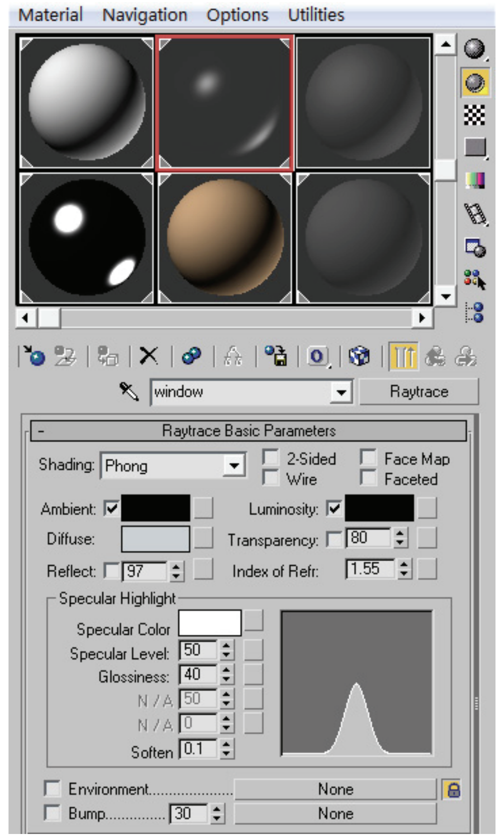
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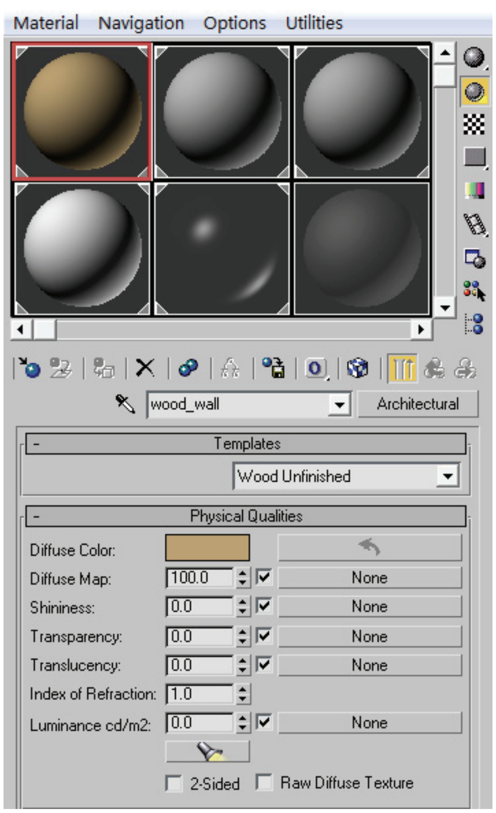
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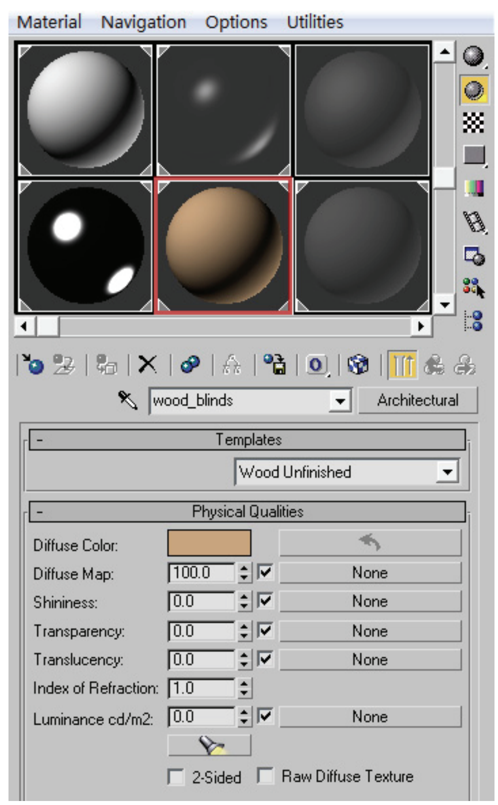
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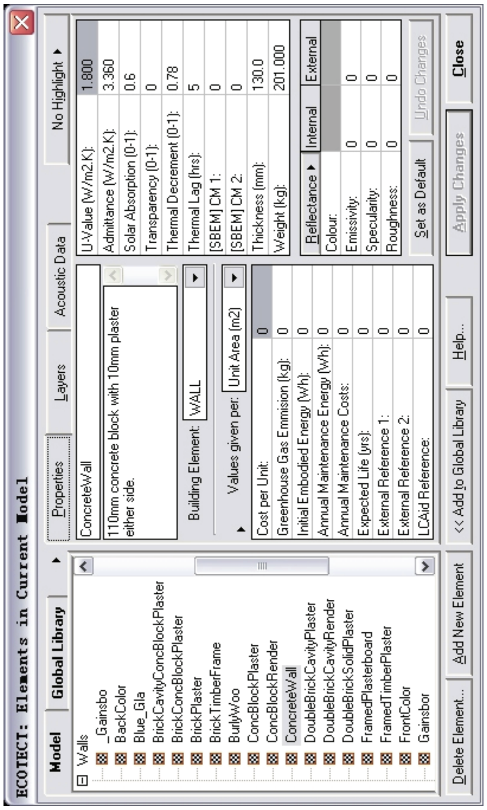
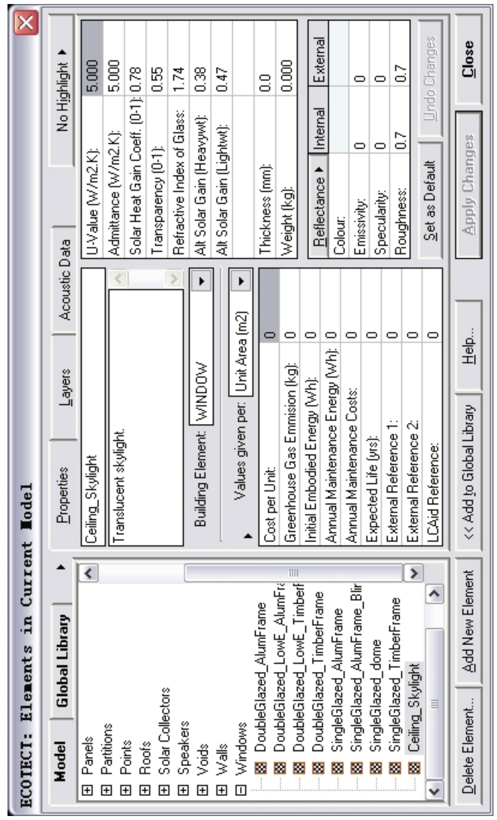
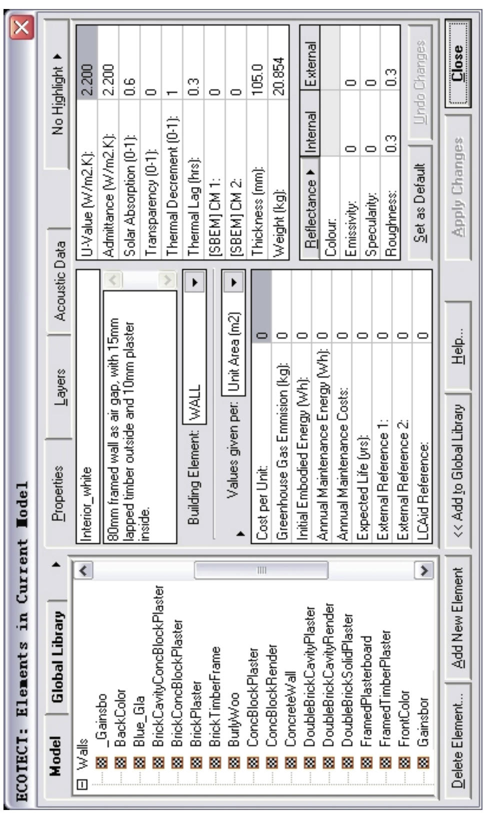
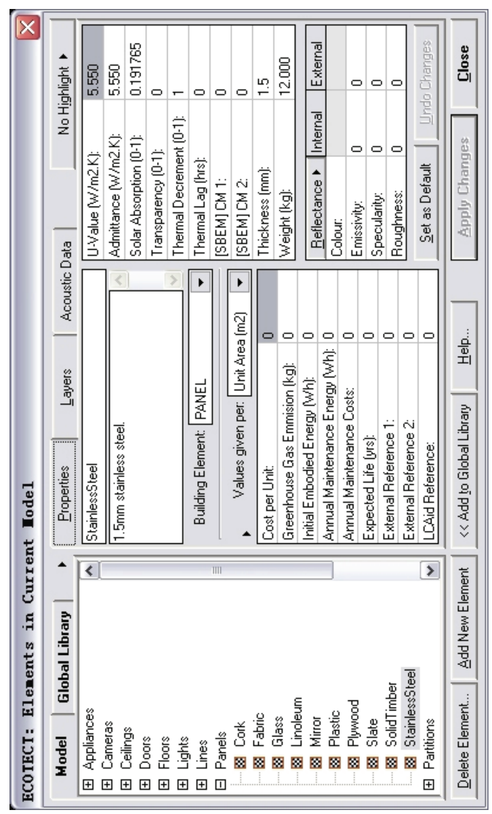
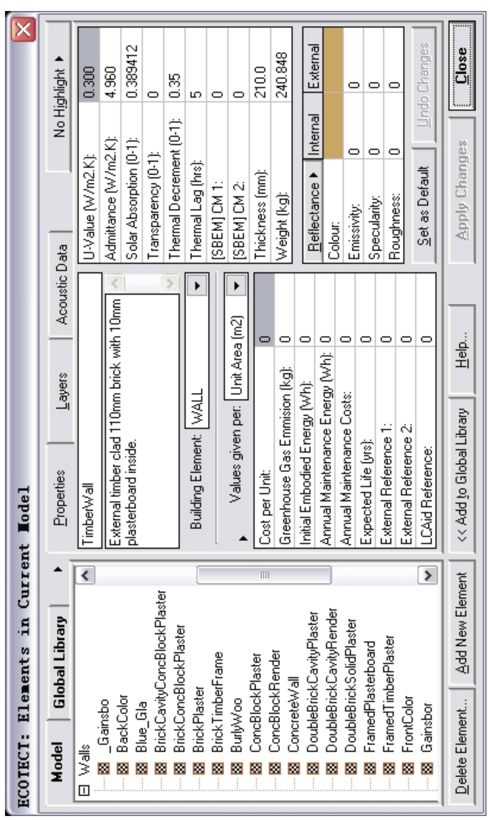
Appendices 2







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TimberWall
External timber clad 110mm brick with 10mm plasterboard inside.
Building Element: WALL
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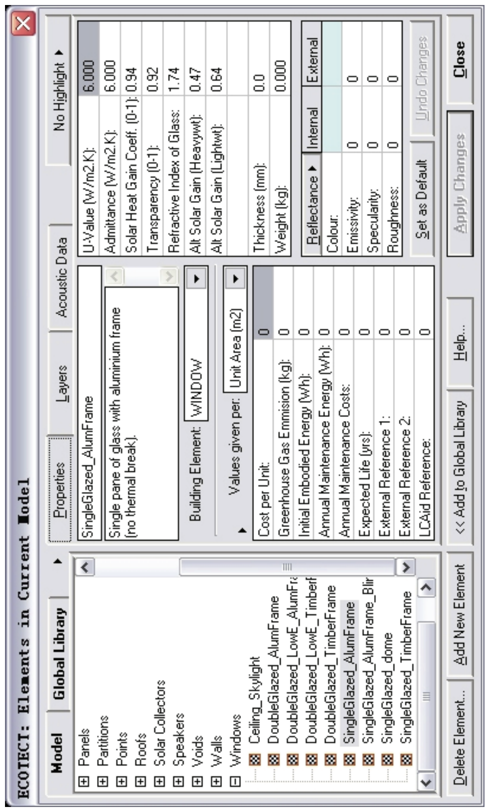
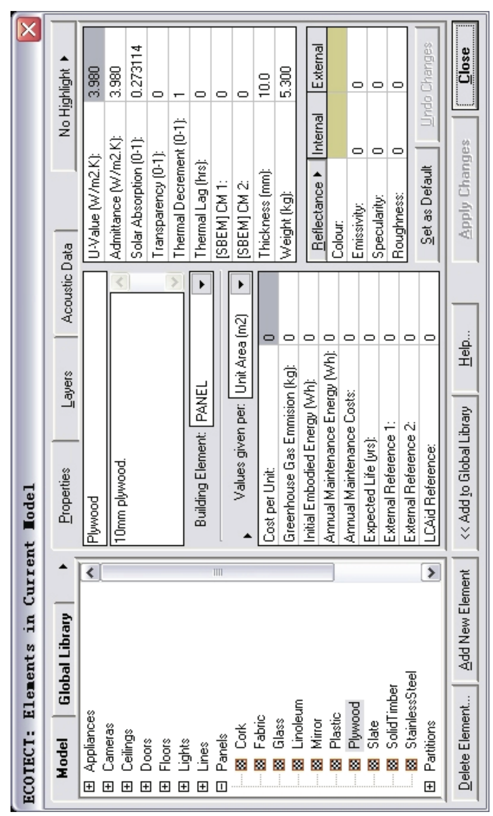
Solar Absorption (0-1): 0.389412
Thermal Decrement (0-1): 0.35
Thermal Lag (hrs): 5
Thickness (mm): 210.0
Weight (kg): 240.848


ECOTECT: Elements in Current Model
SingleGlazed_AlumFrame
Single pane of glass with aluminium frame (no thermal break).
Building Element: WINDOW
U-Value (W/m2.K): 6.000
Admittance (W/m2.K): 6.000
Solar Heat Gain Coeff. (0-1): 0.94
Transparency (0-1): 0.92
Refractive Index of Glass: 1.74
Alt Solar Gain (Heavywt): 0.47
Alt Solar Gain (Lightwt): 0.64


ECOTECT: Elements in Current Model
Plywood
10mm plywood.
Building Element: PANEL
U-Value (W/m2.K): 3.980
Admittance (W/m2.K): 3.980
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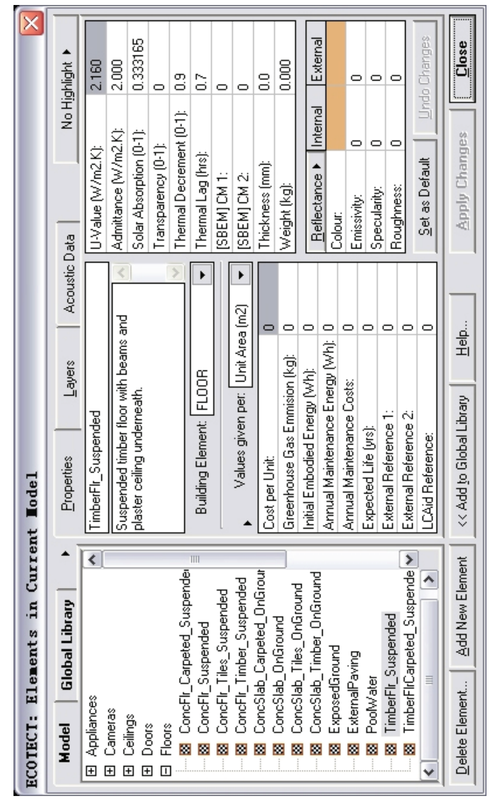
Thermal Decrement (0-1): 1
Thickness (mm): 10.0
Weight (kg): 5.300


ECOTECT: Elements in Current Model
TimberFlr_Suspended
Suspended timber floor with beams and plaster ceiling underneath.
Building Element: FLOOR
U-Value (W/m2.K): 2.160
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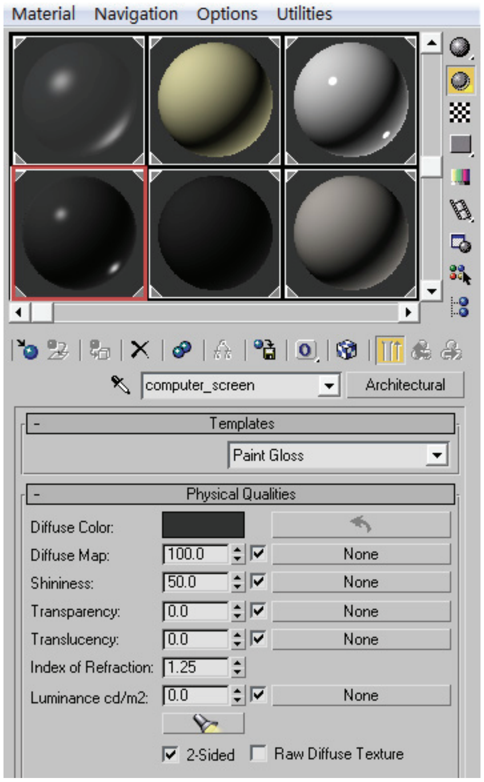
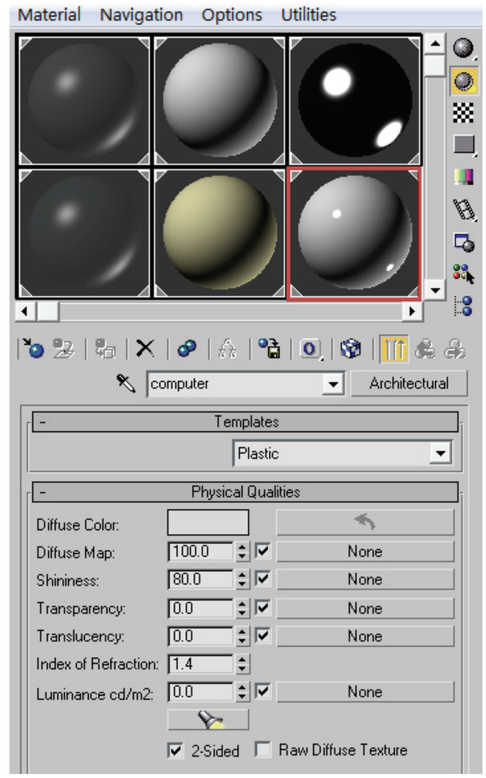
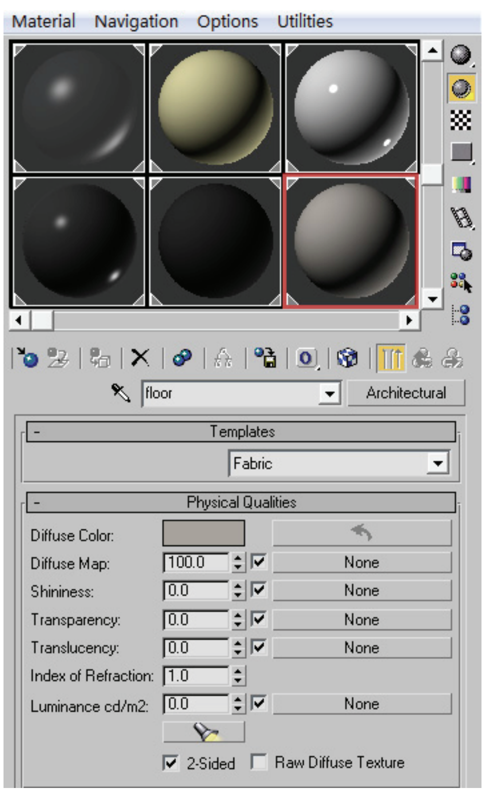
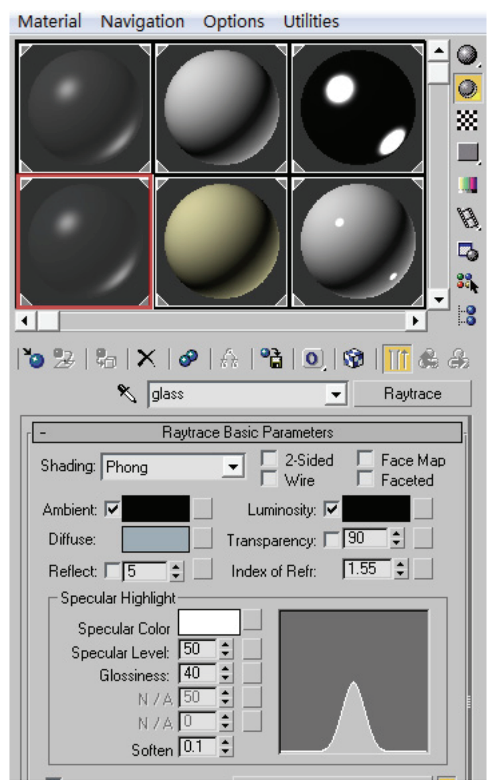
Solar Absorption (0-1): 0.333165
Thermal Decrement (0-1): 0.9
Thermal Lag (hrs): 0.7

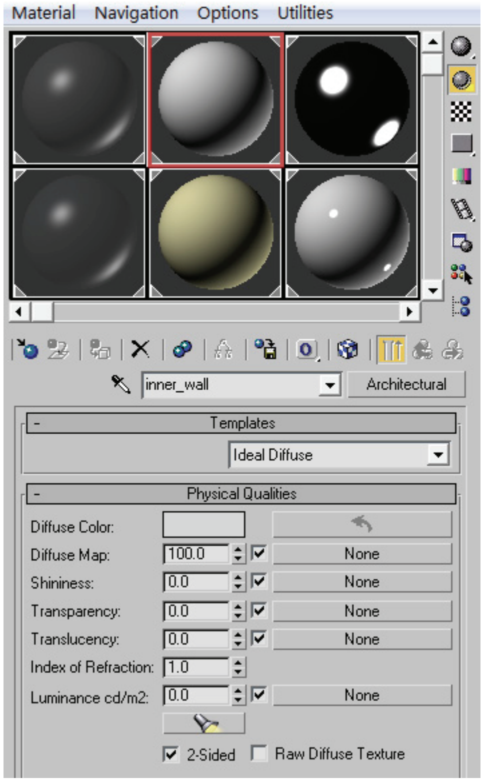
Appendices 3







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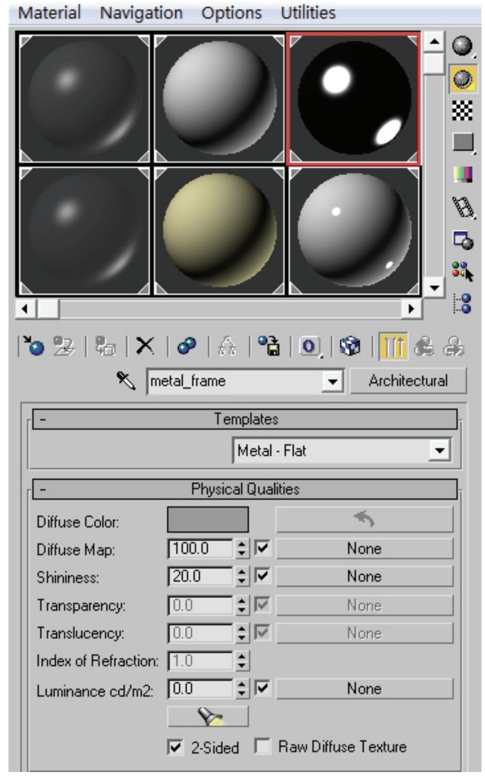
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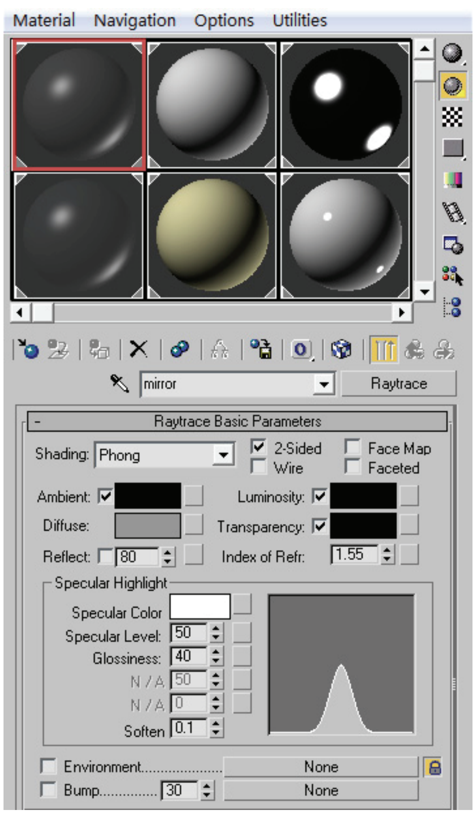
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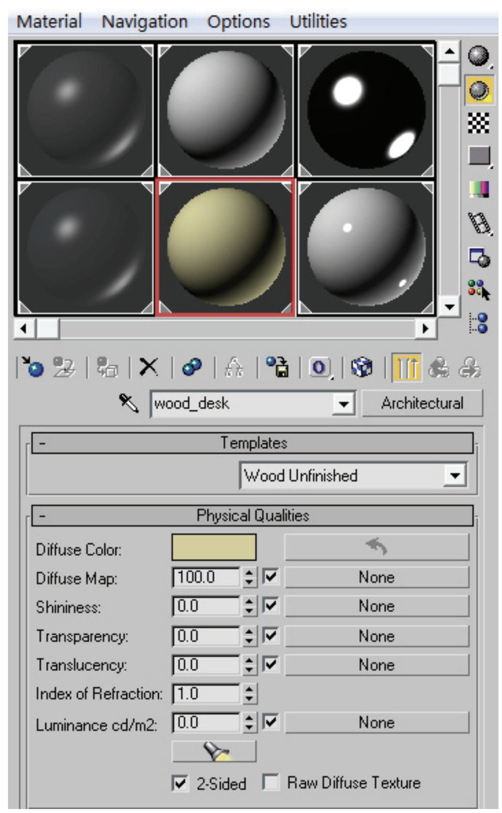
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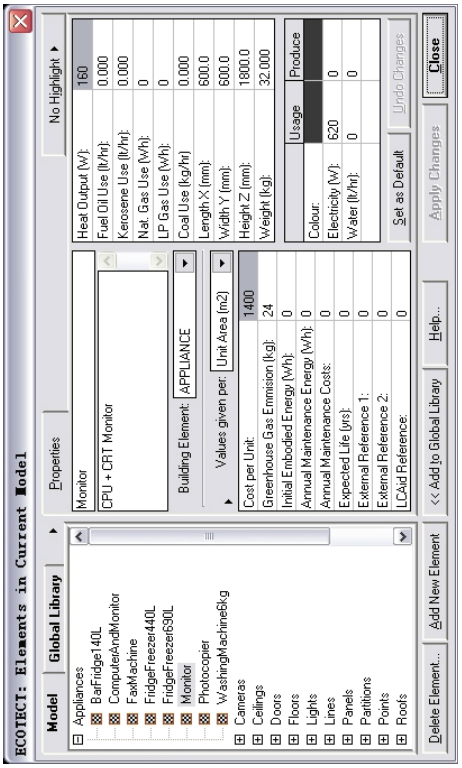
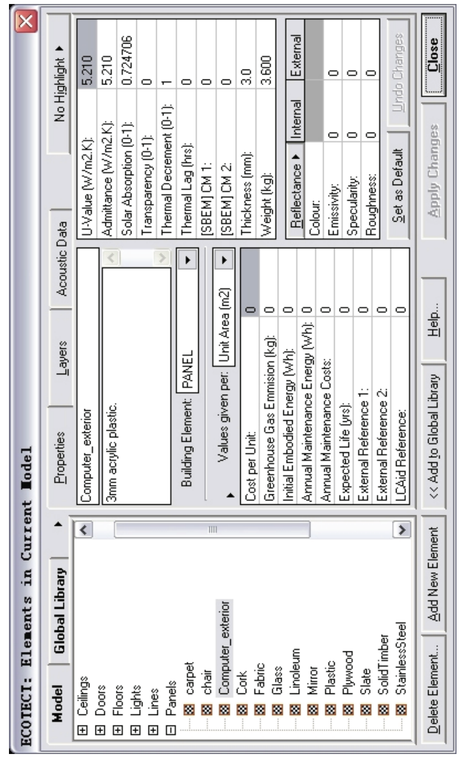
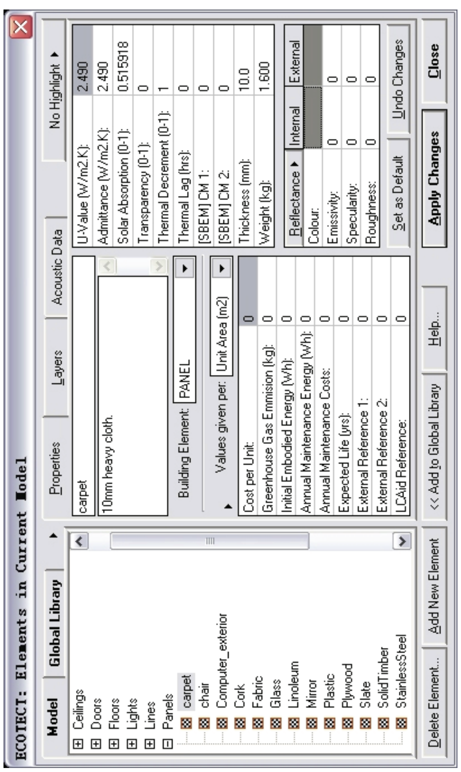
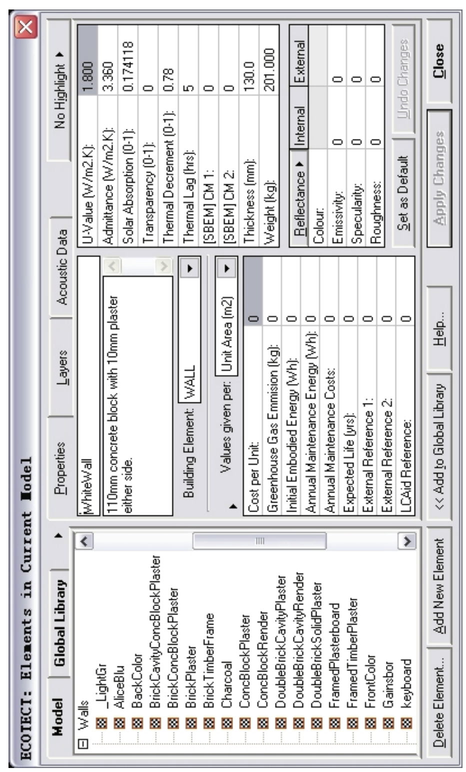
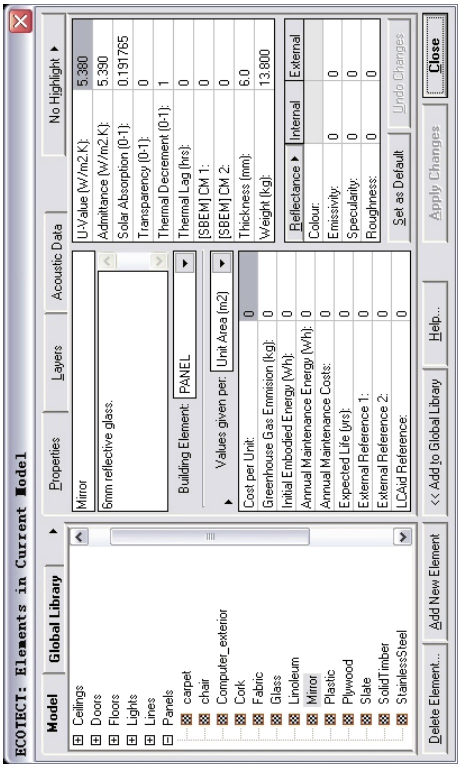
Appendices 4

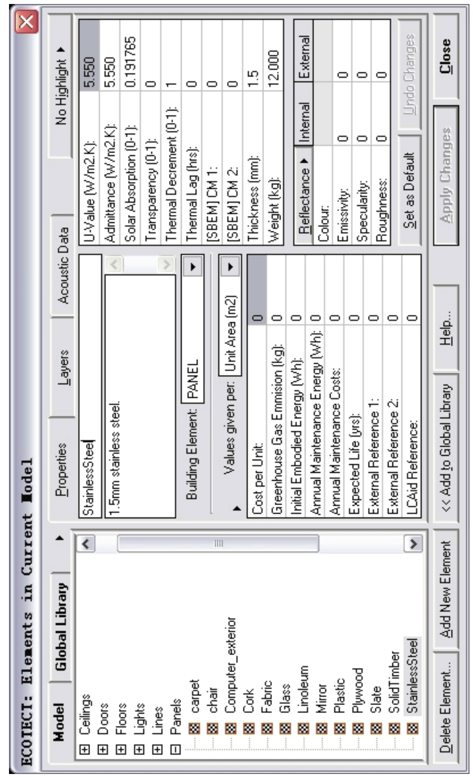


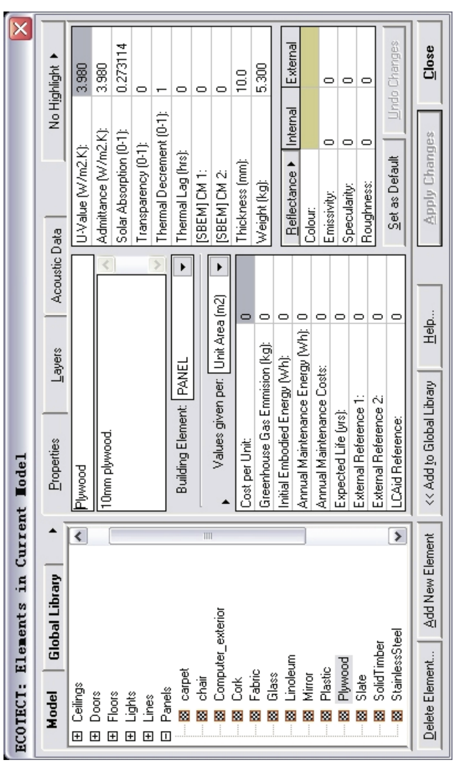


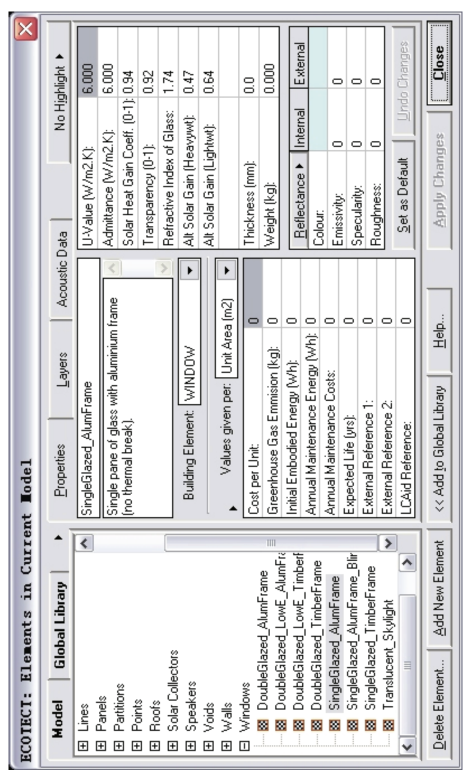








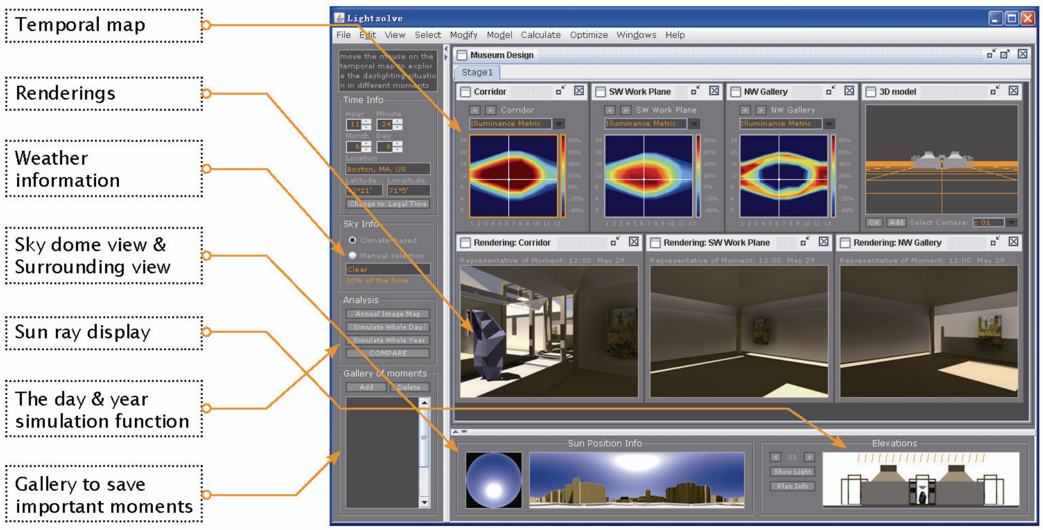




Appendices 5

QUESTIONNAIRE OF THE **LIGHTSOLVE** PROJECT

The aim of this questionnaire is to gather the feedback about the LightSolve project introduced in the presentation. It will help us to find out what is needed by designers to efficiently support the design process. The questionnaire focuses on whether LightSolve, in particular its analysis interface, will be useful to evaluate daylighting performance, find out design issues, and help improve the simulation. What the features that work well in the design process, those that need improvement, and we are also interested in determining the ones we should consider adding into LightSolve to provide better support for the architectural design.



1) What is the ordinary way for you to test whether your design achieves good daylighting performance?

☐ Hand sketch
☐ Physical model
☐ Daylighting analysis tool (e. g. Ecotect)
☐ Computer rendering

2) In your opinion, the temporal maps in LightSolve are useful for:

(1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree)

1 2 3 4 5
☐ ☐ ☐ ☐ ☐ Detecting existing daylighting design problems
☐ ☐ ☐ ☐ ☐ Considering the weather factor in the daylighting design
☐ ☐ ☐ ☐ ☐ Considering the time factor in the daylighting design
☐ ☐ ☐ ☐ ☐ Providing a comprehensive daylighting evaluation

3) Do you think the link between temporal maps and renderings in LightSolve are useful for:

(1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree)

1 2 3 4 5
☐ ☐ ☐ ☐ ☐ Finding out problems within areas you are interested
☐ ☐ ☐ ☐ ☐ Identify the problem type (e. g. too much direct sunlight, too dim)
☐ ☐ ☐ ☐ ☐ Detecting what causes the problem (e. g. sunlight from the skylight)

4) Do you think the combined info of time/date and daylighting performance found on the temporal map is useful for:

(1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree)

1 2 3 4 5
☐ ☐ ☐ ☐ ☐ Guiding the user to browse renderings for GOOD or BAD moments
☐ ☐ ☐ ☐ ☐ Connecting space performances (bright, dim) over time with outside lighting conditions (e. g. sun position, weather)
☐ ☐ ☐ ☐ ☐ As an interactive time/date graph to browse renderings

5) Do you think the weather information in LightSolve is useful for:
(1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree)

1	2	3	4	5	
☐	☐	☐	☐	☐	Connecting the visual effect with different sky types (clear, overcast)
☐	☐	☐	☐	☐	Understanding performance over the year as a result of sky type probabilities
☐	☐	☐	☐	☐	Adapting your design based on the predominant weather condition of the location

6) Do you think the sun ray displayed on the elevation renderings:
(1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree)

1	2	3	4	5	
☐	☐	☐	☐	☐	Is an informative way to dynamically display sun angles
☐	☐	☐	☐	☐	Can relate daylighting performance with different sun angles

7) In what way do you expect the quantitative data (temporal maps) and qualitative data (renderings) together to influence your design process?
(1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree)

1	2	3	4	5	
☐	☐	☐	☐	☐	Find out problems easily and fix them when I still can in the early stage
☐	☐	☐	☐	☐	Explore alternatives I wouldn't have considered based on experience
☐	☐	☐	☐	☐	Be more confident in the performance of my design

8) Do you think the LightSolve analysis interface:
(1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree)

1	2	3	4	5	
☐	☐	☐	☐	☐	Is adapted to the designer's needs
☐	☐	☐	☐	☐	Can be learned quickly with a designer's background
☐	☐	☐	☐	☐	Has an educational potential in terms of acquiring daylighting knowledge

9) In your opinion, the following features in the LightSolve analysis interface can help (check all that apply):

reveal design problems	Evaluate Design Performance	Has an Educational Function	
☐	☐	☐	Temporal map (climate based & goal based)
☐	☐	☐	Renderings updating with the temporal map exploration
☐	☐	☐	The day & year simulation
☐	☐	☐	The annual image map
☐	☐	☐	The weather information in the sky panel
☐	☐	☐	The sky type selection function
☐	☐	☐	Short listing of important moments in the gallery
☐	☐	☐	The comparison panel that displays renderings for comparison

10) Would you like LightSolve to be:

☐ A plug-in for existing modeling tools, such as SketchUp or ______________________
☐ A separate application

11) What are the features you think LightSolve should add in the future (check all that apply)?

☐ Import models from AutoCAD, SketchUp, Rhino, Maya, etc
☐ 2D & 3D Daylight Factor/Autonomy Grid Calculation
☐ Solar Gain & Thermal Analysis
☐ Electric Lighting Analysis
☐ Metrics to access the "ambiance" of a space
☐ ____

12) Additional Comments for LightSolve:

Appendices 6

1) What is the ordinary way for you to test whether your design achieves good daylighting performance?
- Hand sketch
- Physical model
- Daylighting analysis tool (e. g. Ecotect)
- Computer rendering

2) In your opinion, the temporal maps in LightSolve are useful for:
- Detecting existing daylighting design problems
- Considering the weather factor in the daylighting design
- Considering the time factor in the daylighting design
- Providing a comprehensive daylighting evaluation

3) Do you think the link between temporal maps and renderings in LightSolve are useful for:
- Finding out problems within areas you are interested
- Identify the problem type (e. g. too much direct sunlight, too dim)
- Detecting what causes the problem (e. g. sunlight from the skylight)

4) Do you think the combined info of time/date and daylighting performance found on the temporal map is useful for:
- Guiding the user to browse renderings for GOOD or BAD moments
- Connecting space performances (bright, dim) over time with outside lighting conditions (e. g. sun position, weather)
- As an interactive time/date graph to browse renderings

5) Do you think the weather information in LightSolve is useful for:
- Connecting the visual effect with different sky types (clear, overcast)
- Understanding performance over the year as a result of sky type probabilities
- Adapting your design based on the predominant weather condition of the location

6) Do you think the sun ray displayed on the elevation renderings:
- Is an informative way to dynamically display sun angles
- Can relate daylighting performance with different sun angles

7) In what way do you expect the quantitative data (temporal maps) and qualitative data (renderings) together to influence your design process?
- Find out problems easily and fix them when I still can in the early stage
- Explore alternatives I wouldn't have considered based on experience
- Be more confident in the performance of my design

8) Do you think the LightSolve analysis interface:
- Is adapted to the designer's needs
- Can be learned quickly with a designer's background
- Has an educational potential in terms of acquiring daylighting knowledge

9) In your opinion, the following features in the LightSolve analysis interface can help (check all that apply):
- Temporal map (climate based & goal based)
- Renderings updating with the temporal map exploration
- The day & year simulation
- The annual image map
- The weather information in the sky panel
- The sky type selection function
- Short listing of important moments in the gallery
- The comparison panel that displays renderings for comparison

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