Experience of Light:
The Use of an Inverse Method and
a Genetic Algorithm in Daylighting Design

by

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ABSTRACT

Integration of daylight availability in time and architectural space is a critical element in achieving optimal comfort and productivity, as well as in minimizing energy consumption. In recent years, there has been an increase in the demand of the better quality of the built environment. Accessibility and availability of information do not assurance success in design. There is a gap between available information and design team. A critical understanding of the issues that affects design and its process needs to be developed. Successful strategies require the participation of individual users and designers in configuring built environments and needs. Before proposing a new solution, success factors and methodology have been identified.

There are many problems-solving techniques associated with design and delivery systems. Most popular techniques are forward methods and typically employed "trial and error" processes, attacking problems on the front end first. On the other hand, a problem-solving technique called the inverse method seems to be efficient. It starts with designer's goals and then identifies a design to meet those goals. In an effort to provide optimum choices in daylighting design, this thesis emphasizes the use of scientific-knowledge computational tools in the later stages of design employing the inverse method. The genetic algorithm (GA) is applied to search for optimal daylighting design strategies. A new design process has been created, developed, and implemented to increase design process efficiency and creativity. This thesis additionally presents a structured method for defining and evaluating multiple objectives. Objective measures are defined as maximized visual comfort and preferred lighting conditions. The thesis introduces a new daylight glare index (DGIn). Further, a study has been conducted comparing subjective glare response in an office space with the DGIn. Its correlation yields very promising results. Moreover, this research investigates several design problems, GA parameters, and processes for improving design results and efficiency. The most important aspect of GA and its application is the use of computation not as an analytical tool but rather as a vehicle to stimulate learning in the design process. Finally, ideas are presented for future work, based on the potential suggested by our findings.

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This work is dedicated to the memory of Tuan Chutarat, my grandmother, whose gracious support was and still remains a sustaining force in my life.

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Chapter I: Introduction

1.1 Background

1.1.1 Demand of Society

Society has experienced an ever-increasing rate of change since the developments of the Industrial Revolution. The expanding demand for accommodations results in an enlargement of both scale and complexity of building projects. The building design problem becomes more complex; the consequences are that the time available is reduced. Moreover, as far as material and energy resources are concerned, the need for conservation becomes more important these days. The waste not only results in a decrease in the total store of materials available to society in the future, but also in an increase in the pollution of the environment. The energy crises of the 1970s caused us to consider energy efficiency, human factors, and building performance. The economy was transformed from a manufacturing-based industrial economy to a "knowledge-based economy" driven by technological change of production. Thus, much attention has been paid to improve the performance of design.

1.1.2 Designer and Building Performance in Building Design

When designing a building, an architect needs to achieve the best building performance ensuring that the building provides the necessary spatial, thermal, visual, acoustic, air quality, and long-term integrity, while maintaining time, cost, and energy effectiveness. To achieve effectiveness and efficiency of building systems, there is a need for better understanding the relationship between building performance qualities and physiological, psychological, sociological, and economic needs. Disintegration during the design process, i.e. engineers and consultants are consulted at a nearly finished design process, has occurred in which a lack of interdisciplinary effort by a design team is the key to producing an inefficient building. From *Designing the Office of the Future* by Hartkopf, 1993, problems in existing work places and the impact of new technology can contribute to building-related illness or SBS. Common performance problems in work environments are:

- spatial problems of cabling, storage, privacy, and way finding;
- acoustics problems of people and equipment;
- thermal problems of excessive heat, of unbalanced mrt, of local controls not adjusted for the occupancy;
- air quality problem due to low ventilation rates for energy conservation, outgassing from equipment;
- visual problem of glare, brightness contrast, and flicker from light fixtures.

One important issue is that most designers do not want to spend time to analyze a design during the design process since using guidelines, experimentation, or simulation take too long and are too complicated. Moreover, they are not rewarded from the society. In practice, only a few designers do simulation since it requires many inputs and is time consuming and some designers may not know how to deal with all technical terms. Some designers use one or two building guidelines or none.

There is a "gap" between aided-design tools and architects. Therefore, design tools need to be developed, considering factor such as human needs and optimum building performance. However, it is important to note that many aspects in architectural design could not be quantified. They are matters of imagery values, identity and sense of place since people' s experiences and preferences are different (Broadbent, 1973).

1.1.3 Design process

There are several techniques available for problem solving in the design process. This dissertation research will focus on the traditional design process and the inverse method of designing and making decisions. Traditional design processes were analyzed and distinguished by many researchers such as Drucker, Archer, Irwin, Wertheimer, Paterson, and Papamicheal (Irwig, 1977). All models are somewhat closer to the primary human activities which must form the basis of any study of the process. These activities are almost identical to each other but there is a difference in scale, which exists among all models. In common, it can be divided into five stages; defining the problem, analyzing the problem, developing alternative solutions, deciding on the best solution, and conveying decision into effective action. The details will be discussed later in Chapter 2.

However, the problem associated with the traditional design process is that the process is trial and error. Therefore, it is repeated until a desirable design is achieved. It can be time consuming and tedious. Traditional design approaches are not entirely suitable. The existing design process-form follows function and building system follows form-does not seem to be efficient. A new model of the design process appropriate for the design computation needs to be developed.

1.2 Problem Description

Architectural design emphasizes high-standard buildings with sophisticated daylighting systems, because harnessing daylight for indoor illumination provides both energy savings on lighting and psycho-physical comfort in room space. Thus, integration of daylight availability in time and architectural space is a critical element in achieving optimal comfort and productivity, as well as in minimizing energy consumption.

Daylighting design is a hard problem since its properties--such as sky condition, lighting intensity and distribution, colors and radiant energy--vary over time. It is even harder to achieve daylighting distribution into deeper space with less discomfort glare, while also saving money. There are many problem-solving techniques associated with daylighting delivery systems. Most popular techniques are forward methods, attacking problems on the front end first. On the other hand, a problem-solving technique called the inverse or backward method, which seems to be very efficient, has not been applied in architectural design. This method starts with designer's goals and identifies a design to meet those goals.

There is a need for a new design process in the area of architecture. To clearly establish the profound need, this dissertation research first analyzes the general nature of traditional design process in lighting design area. While there is wide divergence in the approaches of different firms and designers, there appear to be common processes that could effectively be redefined and implemented by the application of computer and Internet technologies.

1.3 Objectives

This investigation focuses on using the genetic-algorithm-based system for conceptual design optimization of daylighting design strategies. One of the strengths of the GA method as an optimization technique is its ability to perform optimization across a wide range of problem domains. In particular, the following goals are set:

- To improve the efficiency of the design and learning process using GA as a design tool for daylighting design optimization.

- To increase the diversity of solutions and information produced by a genetic algorithm-based optimization run. It is desirable for one iteration of GA to produce several optimal or nearly optimal designs, allowing the designer to select the "best" design based on other criteria, their judgments concerning the overall solution.

- To apply this approach to examples of problems in order to demonstrate its capabilities and measure its performance.

- To introduce a new design process using GA to perform optimal daylighting designs.

This proposal emphasizes the use of scientific knowledge computational tools in any processes of design in an attempt to provide the optimum results of daylighting design with respect to light level and visual comfort. With this method, practically any rectangular rooms, windows, and light shelf may be optimized. The findings will be useful for the designer and for future studies in applying this tool to approach a comprehensive optimization of the dialogue between cost, performance, and spatial experience. The goal of the optimization process is therefore to find the optimal daylighting design strategies in a fixed region, given certain measures of design performance and a set of design and/or performance constraints. Results derived from this process produce a diverse set of nearly optimal designs, rather than a single best design.

1.3.1 Organization

This research focused on five strategies for daylighting design and process, namely, 1) approaches and design process, 2) discomfort glare, 3) inverse method, 4) design tool, 5) making these strategies usable in the design professions. The remainder of this thesis is organized as follows.

Chapter 2 begins with the investigation of the design process, its trends and available technology. Chapter 3 and Chapter 4 focus on developing and investigating discomfort glare from windows. The new glare index is tested and programmed. Chapter 5 surveys daylighting design tools and establishes vision on a new tool. Radiance is the tool used to calculate lighting level and daylighting glare index. Chapter 6 concerns an inverse method employing GA for optimized window and shading devices. From this method, the objective function is derived for daylighting design strategies regarding lighting quality and quantity in Chapter 7. Chapter 8 integrates the optimization method and the new glare index into a design tool and investigates effects of design parameters. In Chapter 9, all stages listed above are disseminated. It demonstrates the importance of window and lighting design criteria, and opens up the opportunity for wide use and interpretation of my research on methods, techniques, tools, and technology within the design professions. This chapter presents specific examples of how a new approach is developed and implemented in the design process using GA. Finally future work and conclusions are discussed in Chapter 10.

Chapter II: Approaches and Design Process

This chapter provides general approaches and background in design process from researchers and designers point of view. In addition the inverse design approach is introduced. Given this background information, the new trend and vision for the lighting design industry are analyzed and presented.

2.1 Approaches

The work in this dissertation introduces and implements the art and the science of humanity and technology in the design process. Most of the time science uses technique that is separated from concerns of the way of life. In fact, humanity and technology should work together to include the experience of five senses and mind.

2.1.1 The Art of Humanity

It is important to approach, learn, and experience life-style of people who are involved in the design process, especially people who will use such a space. This study introduces concepts of

1. self-awareness,
2. systematic thinking, and
3. direct experience.

The concepts have been implemented as a series of workshops at the IBM Toronto Laboratory. The outcome shown much difference of workers' awareness and thinking before and after the workshops have been conducted.

Awareness is often in accordance with the way people would like things to be, rarely as they really are. It is difficult to see things the way they are because of biases and preferences. When there is awareness of a feeling, the mind will react with like or dislike. Once the like or dislike arise, they influence the thought process and experience is distorted and biased. The knowledge derived from this sort of awareness is not clear because it is not awareness of things as they really are.

The workshops and design games done at the IBM leaded by Turid Horgen of Massachusetts Institute of Technology, encouraged awareness and thinking about their workplace, in search for causes and conditions. We let the workers think and design their ideal workplace. We also discussed and interviewed with them about their background and work processes. I also observed, perceived workers' behavior and their spaces, and worked in their environment just enough to develop the program to know and understand experience as it is, which has been described later in this thesis.

The responses to the first workshop turned out to be worse than we expected. People did not see the values of the process. They thought that the workshop was irrelevant. With an access to the high level employee, and with a good leadership, the second and third workshops have been conducted. The results were much different than the first workshop. They discussed and exchanged their idea about their workplace, helping each other to develop their ideal place in a more systematic thinking such as thinking in terms of causes and conditions or beneficial and harms. People have changed their thought and attitude. They were more supportive and helpful that they realize and value on how good built environment would affect their work style.

Experiences are perceived with an awareness mind, the mind of workers and the mind of observer. This is to see things in such a way as to be able to make use of them, both like and dislike. Whether experiences are pleasant or unpleasant, they can all be used and developed in a beneficial way. To find knowledge through the subject of light, verification through personal experience is the key. It is important for designer to learn users' experience and expose to touch those experience oneself. Once the designer has experienced that effect, he or she could learn it to be appropriate for a certain built environment and context. Lam's idea on awareness is quoted below (Lam, 2001)

> From what I see being built today, I wonder if most of you here today would agree that, particularly in North America, we have hardly begun to take advantage of the energy saving potential of exploiting daylight. Now that the California crisis has begun to create renewed interest in energy conservation, I believe that SUNLIGHTING and good energy design can

> regain a higher priority, if we create delightful as well as energy efficient buildings. Design of lighting for energy conservation and economy without producing pleasant, delightful luminous environments is hard to sell. Poor and wasteful design comes not from lack of hardware or funds, but from the lack of a clear concept of what a good environment is and the values to make necessary tradeoffs. If one really knows what a good environment is, one can more likely achieve one.

2.1.2 The Science of Technology

Throughout the rest of this thesis, the use of science and technology is focused. The study investigated design process, proposed features that could make it more efficient, searched available technology, and disseminated the context found from experience together with latest technology with the hope to make a better living environment. The process began with hypothesis of the new design process, which was derived from the findings from the direct experience in working with a designer and from existing research. Later in this thesis, the new design tool was developed, employed, and tested against the known values and traditional ways.

2.2.3 Research design

The process of this research is straightforward. The observed data were collected, studied, analyzed, and integrated to be employed as a new approach for the prototype development. Then the hypothesis and idea were derived to be tested. Next, simulations and real design process were done. Data collection and analysis were performed and observed. The results from the observation from the analysis and learning process become the data to be used as input to refine the model and prototype. On the practice side of this study, the newly developed tool was implemented to compare design performance in several case studies.

2.2 Design Process

Design can be defined as "an activity aimed at producing a plan which is expected to lead to a situation with *specific intended* properties and without side- or after-effects" (Papamichael, 1993). The attempts to understand and handle design problems have been classified into two generations.

First Generation Approach

This was based on “systems analysis” concept and was initiated during the Second World War. It treats design and planning problems in a rational, straightforward, and systematic way. A designer or a systems analyst understands the problem, gathers and analyzes information, generates solutions, implements the solutions, tests them, and sometimes modifies them. The best design is derived from the optimization among the solution space, the constraints, and the measure of effectiveness.

Second Generation Approach

This approach was initiated in the late 1960s. In contrast to the rational framework of the earlier approach, the second-generation characterizes design problems as “wicked” problems. Wicked problems have no definite formulation. Every formulation corresponds to a statement of the solution and vice versa. The terms “correct” or “wrong” are inapplicable to both formulations and solutions. The approach also denies any necessity for knowledge concerning a design problem. Moreover, a solution is a “one-shot operation,” with no ultimate test to check the appropriateness of the solutions.

As a result, the major contribution of the second generation approach was the realization of design as “an argumentative process,” such that the designer solves problems by considering alternative answers based on advantages (argument for) and disadvantages (argument against). The systems approach, on the other hand, accepts design as a rational activity that calls for, “thinking before acting.”

Neither of the generation approaches to design problems represents actual design practice (Papamichael, 1991). This divergence points to a problem with design practice itself and the way architects are trained. Papamichael observed, described, and analyzed the definition of the design process, breaking it down into design activities with an open mind, rather than attempting to create design in a perceived way. Papamichael claims that a successful description of the design process and accompanying knowledge should be independent from the design domain itself, in other words, they should be as generic as possible.

Design process descriptions by selected researchers are described below.

Archer's Model

1. Agreeing on objectives
2. Identifying the properties or conditions required by the objectives to be exhibited in the end result.
3. Determining the relationships between varying degrees of fulfillment of respective objectives.
4. Establishing the limitations and ideal states.
5. Identifying the laws of the properties.
6. Ensuring that the result lies in the domain of acceptability.
7. Selecting the optimum solution.

Paterson's Model

Paterson claims that the stages of the process are achieved by means of smaller-scale activities. An analysis of the neuro-physiological decision system in the human body has resulted in four activities:

1. Information: the reception and categorization of stimuli.
2. Conclusion: the assessment of the problem, if any, and appreciation of possible courses of action.
3. Decision: the selection of a course of action and the decision to act on it.
4. Execution: the analysis of the possible methods of carrying out of the selected course, and the decision to act on the chosen method.

Papamichael's Model

Design Theory - There are three types of knowledge required during the design process (Papamichael, 1991):

1. Factual knowledge, to specify the as-is situation,
2. Deontic knowledge, to specify the ought-to-be situation, and
3. Instrumental knowledge, to specify how to make transformation, or shift, from 1 to 2.

Further, as mentioned above, the definition of design refers to specific intent, that can be broken down into three activities:

1. The formulation of set of performance characteristics,
2. The generation of plans to transfer from the as-is to the ought-to-be situation (descriptive characteristics of a will-be situation), and
3. The checking for undesired effects (performance of will-be situation).

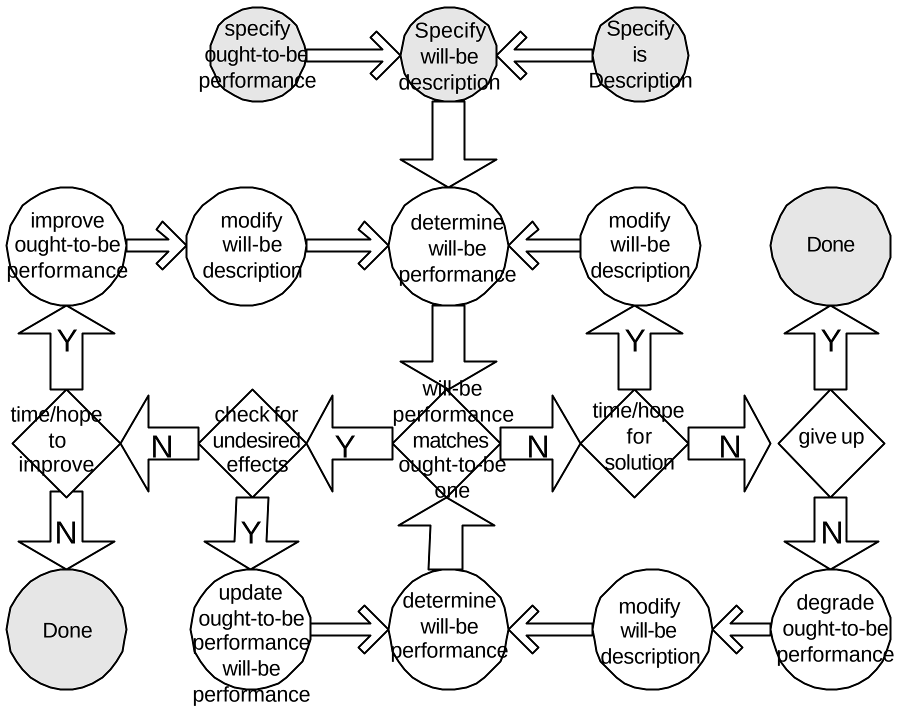


FIGURE 2.1 DESIGN PROCESS FLOW DIAGRAM PROPOSED BY PAPAMICHAEL

Further, Papamichael demonstrated that designing is the equivalent of imaginary living, where life is a continuous design process involving feeling and acting. Therefore, design is not "thinking before acting," nor "feeling and thinking before acting." Rather, it is feeling and thinking while acting.

Drucker's Model

Drucker has created one of the most comprehensive models of the decision-making process. This model employs the following phrases to describe its framework:

1. Defining the problem,
2. Analyzing the problem,

3. Developing alternative solutions,
4. Deciding upon the best solution,
5. Converting the decision into effective action.

As mentioned earlier, all models are somewhat closer to the primary human activities, which must form the basis of any study of the process (Irwig, 1977). These activities are almost identical to one another, but there is a difference in scale, which exists among all models. Luckman omits the first and last of Drucker's stages; Paterson and R.I.B.A. omit the first stage; Archer omits the fourth stage; and Papamichael omits the last stage. This is due to a difference in scale that exists among the proponents of each model. Paterson's proposed process exists at the smallest scale.

Most lighting software tools available today are analysis tools, for which the relationship between the tools and human is presented below in Figure 2.2. They do not assist in generating or refining design options. Instead of an analysis tool, a good design tool should be able to aid designer in refining the design decision during the design process (Figure 2.3).

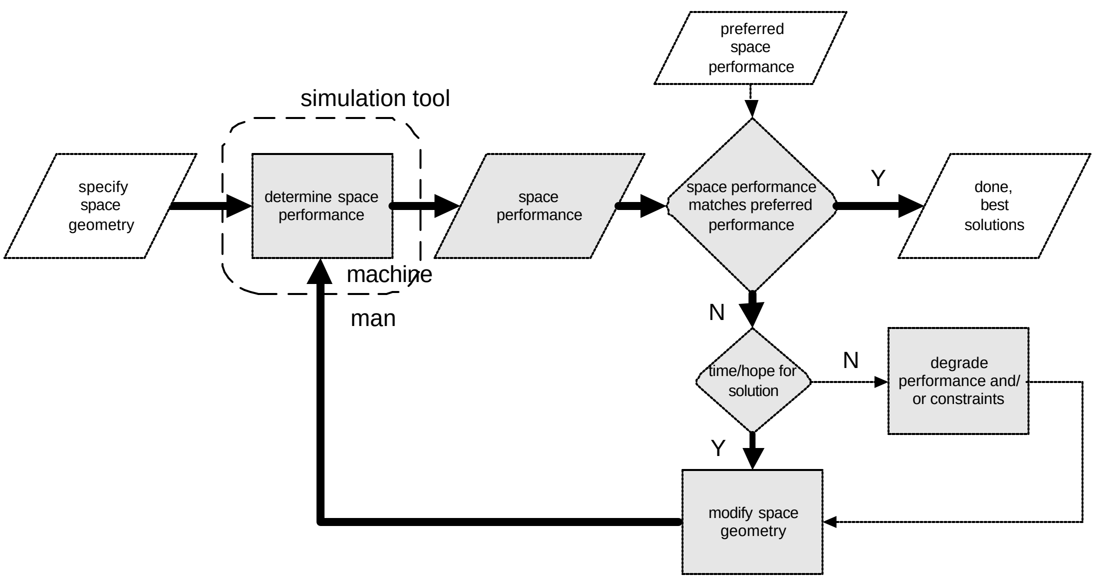


FIGURE 2.2 THE ROLE OF MOST SOFTWARE TOOLS IN THE DESIGN PROCESSES

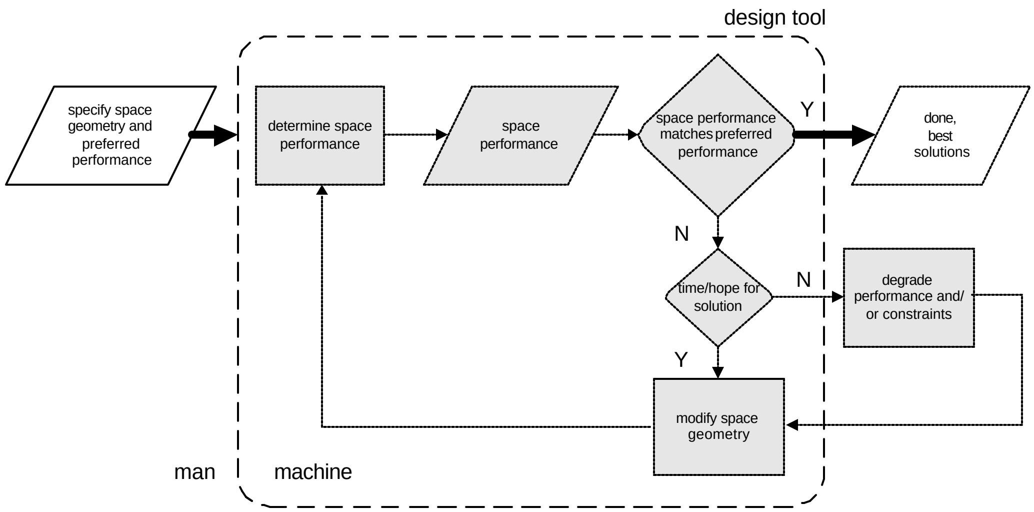


FIGURE 2.3 THE NEW DESIGN PROCESS AND TOOL EMPLOYING THE INVERSE METHOD

One major problem is that currently, software tools available to designers are based on traditional design processes or direct methods, shown in Figure 2.2. To estimate the performance of building designs, the processes force a designer to begin with building geometry, window and opening size and properties, and then simulate and compute a solution or its performance. The process is repeated until the solution closes to the desired effect. Most lighting analysis tools such as Lumen Micro, ADELINE, Lightscape, etc., do not help in the design decision process, but rather evaluate an existing design or determine will-be performance of the design. It is a trial and error process, which is limited by the non-use of directional information. That is, the search proceeds without a sense of appropriate choice or success probability using one path as opposed to another.

According to Papamichael, the fact that computers can be used to assist designers resulted in the development of a design theory. Use of computer-aided design offers a great possibility to "think" (analyze and develop stages in Drucker's model) in the design process. Therefore, the traditional direct method (figure 2.2), the steps of which are repeated during these stages until a desirable design is achieved, can be eliminated and replaced with the inverse method (Figure 2.3).

2.3 The Traditional Lighting Design Process

Similar to traditional architectural design, the traditional lighting design framework is a trial and error process as described below.

1. State problems and research

2. State-activity needs and biological needs

3. Select-desired lighting effects

4. Design and select light sources

5. Check-effects, and other criteria such as brightness ratio, lighting level, and power density if the results fall in criteria ranges.

6. Redesign--Go to step number four, if necessary.

According to Lam, the purposes of good lighting design are to respond to both activity needs and biological needs with respect to their relative importance. Lam analyzed the purposes of lighting, which are summarized in this section (Lam, 1986).

Lighting for visual function

- Task illuminance
- Illuminance distribution in the task area
- Luminance range and distribution within both micro and macro fields with respect to adaptation luminance
- Color rendering properties of light source

Lighting for visual amenity

- Composition of visual lightness and visual interest
- Visual lightness relates to the illuminance and the reflectance of surfaces, particularly the vertical surfaces that surround the field of view.
- Visual interest relates to the composition of light and shade and the illuminance/luminance transition between areas.

Lighting and architectural integration

- The lighting appearance, including the pattern of light and the luminaires, needs to be well-integrated into architecture.
- The transition of visual experience in terms of lighting from one space to another
- The shape and form of space
- The color and surface finish of the major surfaces
- The daylighting performance

Lighting and energy efficiency

- Use daylight wherever possible.
- Use lamps, which are appropriate for the intended purpose and which have a high efficacy.
- Use luminaires, which have a high light output and direct the light where it is required.
- Use electric light where and when it is needed.

Lighting costs (initial, operation, and maintenance)

From experience working with a lighting designer described in Appendix B, today's lighting design processes incorporated the above design purposes and traditional processes using lighting analysis software to refine the design solution. It is considered to be a time-consuming process due to the limitation of availability, accessibility and usability of such a lighting aided-design tool.

As environmental awareness has increased in recent years, so has people's awareness of the importance of light. But unfortunately, lighting designers are trained to follow the traditional design ways. The teaching of lighting design often concentrates on the technical aspects, as mentioned above. The whole concept of the importance of light needs to be introduced in training, and the designer must first understand the overall effect of light on a space, because lighting determines the perception of space and materials (Kale, 1997). The results, or the perceptions of space, need to be introduced first; then the designer can back up determine how the results can be achieved throughout use of available technologies or tools.

2.4 Trends and Vision

The ways people live and work have changed over the years and will continue to change, as new data, knowledge, and information become available. In the work environment, technologies have been developed to meet the demand for increased convenience and productivity. To meet these needs, I have been developing and finding ways for a new design social paradigm to adapt workplaces, now overloaded with information, into a human-friendly environment with support systems that promote increased productivity and creativity as well. Communication and knowledge transferred via the World Wide Web is one of the solutions that can be tapped future to accelerate progress in design.

2.4.1 Lighting industry and market

In the building construction and renovation industry, cost-consciousness and cost cutting often give rise to pricing taking precedence over end performance when decisions are made. Cost overruns on any part of a construction project are often absorbed by "value engineering" of the lighting system. The owner, operator, or builder must incur the expense of installing more energy-efficient lighting systems and other support systems that contribute to a highly adaptable building. However, the tenant or end-user usually receives the savings benefit. As a result, lighting manufacturers are often competitively pitted against each other to supply the least expensive system that will pass the standards set by the installer. Even if there were total agreement among all parties to reach the desired outcome, questions of performance and cost would still abound. The end-user typically receives conflicting recommendations from advisors, who possess inadequate knowledge or only a partial comprehension of how complex systems interact with each other.

The root cause of most of the defects in the lighting decision process is a lack of appreciation for the real benefits of installing the proper system for the application. However, the building lighting industry has both the desire and the capability to supply energy-efficient and energy-effective lighting systems through proper matching of systems to applications. Benefits such as increased worker productivity and lower health care costs can all be realized by thinking in terms of optimized systems instead of lowest initial cost.

2.4.2 Vision

Today, architectural design emphasizes high-standard buildings with sophisticated lighting systems, because good building system design provides energy savings, better environmental quality, and psycho-physical comfort in room space. But despite the availability of applicable research and appropriate technologies, designers and end-users usually do not recognize or use these advanced systems, ignoring them for many reasons. This entrenched stance incurs high costs, however, since traditional design tools and processes are time consuming. As a future work of the dissertation, the research delivers work prototypes and information to bridge gaps among manufacturers, researchers, designers, end users and owners.

It is a useful approach to applying state-of-the-art of optimization in design and its framework because it can provide insight into the possibilities and challenges of computation in architectural design. As a result, people will be able to understand, value, and utilize the tangible, personal benefits provided by advanced and building-appropriate lighting systems. The web should be treated as a fundamental shift that will change the traditional lighting industry for better work quality and process. The site should be designed and structured to reflect the users' tasks and their view of the information space.

The future will initiate a new community with industry to determine how lighting systems will meet all above challenges, using the web to guide the community to the new technologies and business practices that will meet their needs in today and tomorrow's buildings. The site should be a place to educate, communicate and exchange knowledge as well as to be resources and incentives for lighting technology development.

Chapter III: Daylighting Design, Calculation Models, Criteria

This chapter describes practical and technical techniques in daylighting design. It deals with daylighting issues, processes, and calculation models. Finally, the selected calculation method and criteria used in this research are determined.

3.1 Daylighting Issues

Daylighting design has a critical impact on human beings, since lighting can affect people's performance through its effects on mood, motivation, behavior, and well-being. For instance, the more positive the prevailing atmosphere, the more likely people are to express positive judgments of others and to engage in helping behaviors. Moreover, people's aesthetic judgments are determined primarily by the perceived brightness and color of the overall space. For example, people tend to perceive their cubicle workspaces as "too dim," even when they are at recommended illuminance levels. This common perception is apparently due to inadequate brightness of vertical surfaces. The vast majority of research on lighting concludes that luminous conditions that are more appropriate for the task at hand will promote higher performance (Pacific Gas and Electric Company, 1999).

In solving practical problems, a designer often wants to optimize more than one performance factor at the same time. The measures may conflict with one another, and it can be unsatisfactory to combine them into a single optimization objective, or reduce them in some way so that only one is optimized. The most common measurement used today is cost. An example of prevalent conflicting objectives might include maximizing natural light and keeping air-conditioning costs low. However, at least five primary issues need to be addressed and understood before daylighting can be utilized. These design issues are:

- The need for a daylight- and sunlight-availability database for analyzing lighting and energy performance characteristics of the system and building

- The need for a systematic method of describing the daylighting concept (in order to develop design intuition about the best ways to use daylighting in buildings)

- The need for comprehensive methods of analysis that include all aspects of system performance (illumination, energy, and visual comfort)

- The need for a method of integrating daylighting and electric lighting

- The need for a better understanding of who has responsibility for the design of the daylighting system—an architect, an engineer, a lighting designer, a daylighting consultant, or a combination of these practitioners. (Robbins, 1986).

3.2 Daylighting Design Process

According to Robbins (1986), the daylighting design process can be categorized into seven steps, which are listed below:

- Predesign analysis
- Schematic design
- Design development or final design
- Documenting
- Bidding
- Construction
- Postconstruction evaluation

During the predesign analysis process, daylighting-related information should be clarified, collected, analyzed, and processed to ensure proper consideration for daylighting during later stages. Necessary information during predesign analysis includes climatic data, daylight and sunlight availability data, and other relevant information such as utility rates, work schedule, etc. (Robbins, 1986). It is necessary to make two daylighting-related decisions during the first design step: 1) whether or not daylighting is a viable lighting alternative for the building; and 2) if so, what information must be provided to site planning and programming to allow for the use of daylight in the building (Robbins, 1986).

During schematic design, there should be some concern for the way in which daylight interacts with the environmental system, that the daylighting concept should not be overdesigned during this phase. In the other words, some estimates should be made, but there is no need to calculate many details on the structural system, HVAC system, and energy performance (Robbins, 1986). The purpose of this design stage is to establish zones, type of HVAC system, overall bay sizing, and lighting effect, without determining final size and detailed elements.

During the final design stage, the daylighting concept is transformed into a daylighting system. This phase includes the arrangement and sizing of daylighting apertures and spaces in the building. The daylighting system should undergo detailed system design and analysis, including establishing final dimensions for the apertures, specifying glazing type, and selecting solar controls and other variables as they relate to architectural form. The final design phase may include design tools such as building performance simulation and physical modeling, to help establish overall building performance. It is essential to develop an understanding of the relationship between building performance characteristics and all needs.

3.3 Daylighting Calculation Models

There are many ways to analyze a daylighting system such as the lumen method, daylight factor method, radiosity method, ray tracing method, and physical model method to evaluate lighting performance characteristics in terms of quantity and quantity; psychological and physical analysis or human perception and comfort analysis; and economic analysis or lighting energy use, tradeoff analysis of energy use, and cost analysis. This research concentrates on lighting quantity performance and visual comfort analysis that are recommended by the IESNA. There are two approaches to generating photorealistic images -- digital pictures that are difficult to distinguish from real photographs -- in computer graphics. The first approach involves ray-tracing techniques; the second approach is radiosity. Radiosity and ray tracing methods of analysis are presented below.

3.3.1 Ray tracing vs. Radiosity

Ray tracing algorithm is one of the first global illumination algorithms works by tracing rays backward, from the eye position, to the light source. The model description provides the reflectivity of the surface, not the amount of light falling on the surface. Thus, there is no form factor involved in this process. Ray tracing is a very accurate illumination algorithm because of the large range of lighting effects it can model. However, the main disadvantage is that the process is slow and it does not account for diffuse surfaces, which is very important characteristic of global illumination.

In the early 1960s, the radiosity technique has been developed in thermal engineering for determining the exchange of radiant energy between surfaces in an enclosure at thermal equilibrium. This theory assumes that all emission and reflection processes are ideally diffuse (Lambertian). To perform a radiosity analysis, the environment is divided into discrete surface areas, patches, or elements. Then, light is distributed to all surfaces. Depending on the characteristics of the surface material, some of the energy is absorbed, while the remaining energy is reflected to the other surfaces. The process continues until the energy in the environment reaches the equilibrium state. Therefore, the accuracy depends on the number of iterations and how small the elements are subdivided.

A good program should have these two algorithms, ray tracing and radiosity, available. Users can either select one of those techniques or both to calculate depending on how much time and how accurate required. Radiosity is in a sense the complement of ray tracing. Ray-tracing techniques excel in the rendition of point light sources, specular reflections, and refraction effects. Radiosity methods accurately model area light sources, diffuse reflections, color bleeding effects, and realistic shadows. Whether to choose ray tracing or radiosity will depend in part on what effects are more important in those images.

Radiosity has the advantage of view independence. Using ray-tracing techniques, the number of ray-surface intersection calculations can increase geometrically with the complexity of the scene. Change a point of view and the designer typically has to start from scratch to generate a new image. With radiosity, however, the designer only needs to perform the lighting calculations once for a given environment. Once they have been completed, the designer can quickly render a view of the environment as seen from any position and orientation. However, the radiosity algorithm has the following disadvantages: the 3D mesh requires more memory than the original surfaces, the surface sampling algorithm is more susceptible to imaging artifacts than ray tracing and does not account for specular reflections or transparency effects.

3.4 Lighting Design Criteria

To achieve a good visual environment, several design imperatives must be considered. One underlying fundamental that must guide design is surface illumination. That is the way in which surfaces are illuminated is more important than the amount of light that strikes them, a fact that affects visual perception in important ways. Many studies on lighting conclude that daylight is preferable to artificial light because of its quality. Daylight is the light source that most closely matches human visual responses and it therefore seems to provide the best visual environment. To fulfill the visual comfort requirement, which is the goal of this study, visual quality and visual quantity, should be considered during the design process. They are described below.

3.4.1 Visual Quality

Quality of lighting is the phrase used to describe all factors in a luminous environment that are not directly connected with the quantity of light, as stated below.

> Visual effectiveness is influenced by the variable character of daylight, it would appear that any daylight measurement should apply to particular conditions at a particular moment. Fortunately, these changes are relatively slow and do not affect the visual impression of light quantities; in fact, the human eye adapts itself continuously to changing light patterns. However, due to daylight changes as a function of sky conditions, absolute measurements are not directly indicative of the actual building performance (Baker, Fanchiotti, and Steemers, 1993).

- **Glare**

The CIE defines glare as the "condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or extreme contrasts." According to the Illuminating Engineering Society of North America, discomfort glare is a sensation of annoyance caused by extreme brightness or a non-uniform distribution brightness in the field of view (IESNA, 1993). Although glare is not necessarily a design issue all the time, it becomes critical when certain viewing conditions occur.

Glare is a function of the size and number of apertures, the brightness of the source of light seen through the apertures, the brightness of ambient light, and the location of the apertures in relation to the field of view (IESNA, 1993). Problems with daylight glare most often occur in side-lighting schemes, especially in schemes that allow direct sunlight into a room, or that provide occupants a direct view of the sky and the work surface at the same time (Boubekri and Boyer, 1992). Thus windows are potential glare sources, since they occupy a large portion of the visual field. The glare from a vertical plane seems to be crucial. Discomfort glare is a result of the contrast between the window and adjacent walls and ceiling. It is therefore an important factor in window design and strategy, because it affects the choice of glazing material and the reflectance and color of interior surfaces.

Studies of discomfort glare have been conducted for relatively small-sized sources and with artificially lit rooms: IES Glare Index (IES GI), Discomfort Glare Rating (DGR), and Visual Comfort Probability (VCP). The VCP is the percentage of people who would be expected to find the cumulative glare sensation, represented by the DGR, acceptable. The IESNA states that if a VCP value of greater than 70% occurs and the luminance uniformity and distribution of luminaires are within certain limits, then the discomfort glare is acceptable (IESNA, 1993). The DGR and VCP have some limitations, and are not applicable for a large glare source, as stated below.

> This system was tested and validated using lensed direct fluorescent systems only. VCP should not be applied to very small sources such as incandescent, to very large sources such as the ceiling in indirect systems, or to non-uniform sources such as parabolic reflectors (IESNA, 1993).

The degree of discomfort glare due to viewing the sky through a window, can be treated as a large source, and can be predicted from a modified Glare Index known as the "Cornell formula" (Chauvel, Collins, and Dogniaux, 1982). From studies by Hopkinson, it was found that the correlation between the observations and glare predictions was not as good as that obtained in studies on glare from artificial lighting (Hopkinson, 1972). Moreover, it appears that the glare from daylight sources, represented by the Daylighting Glare Index (DGI), is better tolerated than glare from artificial lighting, as represented by IES GI.

It is important to note that all glare evaluation systems available today, including DGI provided in Radiance, are derived from artificial sources. They are not recommended for use with daylighting. There is a difference between the glare a viewer experiences from a real window and the glare that is experienced from a simulated window. This difference is partly attributable to psychological differences in the visual content of the field of view, and in real daylighted spaces. Further, the results are based on very few experimental data. No index has actually been recommended for assessing discomfort glare caused by a large window, in daylighting conditions.

- **New Glare Evaluation Method**

A new study, conducted by Nazzal, under real daylighting conditions, proposed a new glare evaluation formula (Nazzal, 1998). This method measures illuminance instead of luminance, and the data used are based on Chauvel's modification of the Cornell large-source glare formula to calculate daylight glare indices (DGI_N), as described in Chapter 4. The background and window luminances were rejected in this method, because a source as large as a window covers such a large area on the retina that it cannot be clearly distinguished from the background. Nazzal's new method is included and developed in this dissertation, since it is the most reliable and accurate system. It has been modeled and tested in Radiance by the author.

- **Luminance Ratio (LR)**

Luminance ratio, or brightness ratio, is a measurement commonly used to refer to the strength of the sensation people experience when they view surfaces. It is determined by the measurable luminance. When surfaces with strongly contrasting luminances are present at a workstation, the eyes must adjust to different luminances, which causes eye fatigue and thus reduces the ability to work. To achieve good visual performance, IESNA recommends the following brightness ratios within the field of view. Ideally, the brightness ratios should fall within the following range of acceptability:

- Between task and darker surroundings and/or adjacent surroundings: 3:1
- Between task and remote darker surfaces: 10:1
- Between light sources and surroundings: 20:1
- Maximum contrast (except if decorative): 40:1
- Highlighting objects for emphasis: 50:1
- Desirable anywhere in the field of view, no greater than: 10:1 (IESNA, 1993).

- **Color Rendering**

Variability is the characteristic of natural light that most distinguishes it from artificial light as a light source. Natural light varies in magnitude, spectral distribution, and emission at different times and in different locations. The spectrum of daylight varies with the nature of the atmosphere through which it passes. The correlated color temperature can vary across a range from 3000 K to 40000 K. In practice, it is common to take an appropriate color of daylight as a reference source. Thus the color rendering of daylight is considered the best source of light and is also considered nearly perfect.

- **Visual Noise**

Perceptions are interpretations of information, and thus the information sought should be pleasant. Things that interfere with visual comfort or rest are considered visual noise. Therefore, the design of the window system should take into account design elements such as shape, number, color, composition, and location of windows, as well as shapes cast from shadows. During design, the accentuation of visual noise should be created in a way that will enable the designer to ultimately reduce it.

3.4.2 Visual Quantity Criteria

In general, adequate illuminance for the visual task with minimal glare is considered one important factor in successful daylighting design. The Illuminating Engineering Society of North America established design procedures for selecting illuminance based on factors that are important to visual performance. The factors that a designer needs to assess in selecting target illuminance are:

- Type of activity within a space
- Characteristics of the visual task
- Age of occupant
- Importance of visual performance in terms of speed and accuracy
- Reflectance (IESNA, 1993).

Consideration of these factors is systemized into four steps:

1. Define the visual task: The type of activity for which the illuminance is being selected is defined. At the same time, the plane in which the visual task will be performed is determined.
2. Select the illuminance category: Nine illuminance categories are established by IESNA. Each of these nine categories is associated with a range of three target illuminances, which can be found in the IESNA 1993 lighting handbook.
3. Determine the illuminance range: Every illuminance category has a corresponding range of three target illuminances, depending on the nature of the task.
4. Establish target illuminance: Target illuminances are established differently by considering room surface reflectance and occupant ages. Then the designer determines weighting factors and finally selects the target illuminance ranges by considering the sum of the weighting factors.

Design quality and quantity criteria used in this research are daylighting glare index and illuminance level. The other issues—such as patterns of shadow, visual noise, and color rendering—are left for designers to determine when making their design decisions. The DGI and illuminance levels are the most crucial criteria, since they strongly affect visual perception and performance. Further, illuminance levels are widely used by lighting designers and architects.

Chapter IV: A New Daylight Glare Evaluation Method

If daylight is usually the preferred source of light, very high daylight availability in an interior environment is often contrary to optimal visual conditions. Excessive sunlight appears to create a whole host of psychological reactions. Glare is one of the major factors affecting visual comfort. If that problem can be solved, not only will the visual comfort be improved but also the savings of electric energy can be increased due to the improved efficiency of the use of daylight for indoor illumination. The latest glare evaluation methods have been useful in prediction of discomfort glare from artificial light sources but only a few formulae have been proposed for discomfort glare of daylight origin. None of these methods predicts discomfort glare from daylight or specifically from direct sunlight.

It is difficult to apply the glare index formula obtained from a laboratory experiment. However, the equations of Hopkinson and Chauvel and all existing glare indices are based on experiments using artificial light in the room during the daylight glare measurements. Thus it is difficult to evaluate glare caused by windows. Successful lighting and ergonomic design of workplaces requires a proper method and process for predicting glare. The principal aim of this work was to develop a new, mathematical glare evaluation method that would be valid for direct sunlight, and to implement the new glare algorithm into a computer program using Radiance that provides luminance values. Consequently, it would be possible by this method to define with ease and reasonable accuracy the glare level caused by windows in a room space in the form of a daylight glare index and to assist the selection of daylighting systems.

4.1 Existing Daylight Glare Index (DGI)

The degree of discomfort glare due to the sky seen through a window can be treated as a large source, and can be predicted from a modified Glare Index known as the “Cornell formula” (Chauvel, Collins, and Dogniaux, 1982). Chauvel modified the Cornell formula as shown in Eqn.4.1.

$$G = 0.478 \sum \frac{L_s^{1.6} \times \Omega^{0.8}}{L_b + 0.07 \times w^{0.5} \times L_w} \qquad (4.1)$$

where	G	is Glare index
	L_s	is the source luminance: luminance of the patch of visible sky, of the obstructions and of the ground seen through the window [cd/m^2]
	L_b	is the background luminance: luminance of the interior surfaces [cd/m^2]
	L_w	is the window luminance [cd/m^2]
	ω	is the solid angle subtended of the source at the eye [sr]
	Ω	is the solid angle subtended of the source modified for the effect of the position of its elements in different parts of the field of view

The Daylight Glare Index, DGI, can be calculated as the logarithm of the Glare Constant, G:

$$DGI = 10\log_{10} G \qquad (4.2)$$

It appears that the glare from daylight sources represented by the Daylighting Glare Index (DGI) (Eqn.4.3) is more tolerated than glare from artificial lighting as represented by IES GI. The relationship for the two measurements can be expressed by the equation:

$$DGI = \frac{2}{3} * (IESGI + 14) \qquad (4.3)$$

The IES Code for 1973 recommended glare indices and the limiting values corresponding to the criteria of acceptability as presented in Table 4.1.

TABLE 4.1 COMPARISON OF GLARE INDICES FOR ARTIFICIAL LIGHT (IES GI) AND DAYLIGHT (DGI)

Glare Criterion	IES GI	DGI
Just imperceptible	10	16
	13	18
Just acceptable	16	20
	19	22
Just uncomfortable	22	24
	25	26
Just intolerable	28	28

It is important to note that all glare evaluation systems available today, including DGI provided in Radiance, are derived from experiments using artificial light sources. They are not recommended for use with daylighting. There is a difference between the glare experienced from a real window and the glare experienced from a simulated window which is also due to the psychological difference in the visual content of the field of view, and in real spaces with daylight. Besides, they are based on very few experimental data. No index has actually been recommended for assessing discomfort glare from daylight due to a large window.

4.2 The New DGIn

4.2.1 Parameters

The DGI_N method is based on Chauvel's modification of the Cornell large-source glare formula (Eqn.4.1) to calculate daylight glare indices in ordinary work and habitable rooms. The Cornell formula of Hopkinson (Eqn.4.4) takes the source luminance and the background luminance into consideration. The parameters in the modified version by Chauvel are the source luminance, the window luminance, and the background luminance:

$$G = 0.478 \sum \frac{L_s^{1.6} \times \Omega^{0.8}}{L_b + 0.07 \times w^{0.5} \times L_s} \qquad (4.4)$$

where

L_S	is the source luminance [cdm^{-2}]
L_b	is the background luminance [cdm^{-2}]
ω	is the solid angle subtended of the source at the eye [sr]
Ω	is the solid angle subtended of the source modified for the effect of the position of its elements in different parts of the field of view [sr]

However, the monitoring protocol to measure the needed parameters has not been presented in either the publications of Chauvel or Hopkinson. Moreover, the summation sign in the two formulae makes both methods mathematically anomalous; since summation has to be over solid angles in the field of view. Ω should be to the power of 1, in other words, the summation must be proportional to the solid angle as suggested by Nazzal.

When compared with each other, both Chauvel's method and the DGI_N method use the basic glare parameters: size of light source, luminance; and, position of the light source in the field of view. The equations utilized in the two glare evaluation procedures contain necessarily similar components but differ fundamentally in the determination of the sources of luminance and solid angles. In the new DGI_N method, the apparent solid angle $w_{\mathbf{N}}$ subtended by the window, and the solid angle $W_{\mathbf{pN}}$ subtended of the source are modified to include the effect of the observation position and configuration factor. The weight of the background luminance is large in Chauvel's method, which affects the average luminance of the visual field or adaptation luminance. A large glaring source such as a window also covers too large an area on the retina to be clearly distinguished from the background. Therefore the background luminance cannot be accurately defined and was rejected in the DGI_N method.

Instead of using the background luminance, the term of adaptation luminance was introduced because of the greater impact the immediate surrounding luminance has on discomfort glare sensation in comparison to the background luminance. The adaptation luminance includes the contribution of the source. The parameters here are:

1. the window luminance: the source luminance,
2. the adaptation luminance: the luminance of the surroundings including reflections from room surfaces,
3. the exterior luminance: the luminance of the outdoors, caused by direct sunlight, diffuse light from the sky and reflected light from the ground as well as other external surfaces.

4.2.2 Calculation procedures

The room can be occupied or unoccupied, with or without shading devices in the window, but the monitoring protocol assumes the room to have only vertical window(s). There are no limitations for the window size, shape, position, or orientation. Because the measurement position is in the same horizontal plane as the center of the window, the method is not, however, recommended for windows directly under the ceiling such as clerestory windows in an industrial hall. This is because the difference between the measurement position and the position of the observer's eyes would be too big. In that case, the measurement could predict less glare than the observer would perceive when looking up towards the window and a brighter part of the sky. On the other hand, this kind of windows would be at the periphery of the visual field and would be notably less glaring. In regard to daylighting calculations, no artificial lighting is permitted but both daylight and sunlight can be measured. This is an advantage over the other daylighting calculations which all have assumptions not to include direct sunlight into a room (Nazzal, 1998). The degree of discomfort glare is reflected in the DGI_N method. As stated earlier in the previous section, Ω should be to the power of 1. This can be done as stated below:

$$10\log_{10}\left(L_{exterior}^{1.6} \times O_{pN}^{0.8}\right) = 8\log_{10}\left(L_{exterior}^{2} \times O_{pN}^{1}\right) \tag{4.5}$$

The DGI_N can be calculated as:

$$DGI_N = 8\log_{10}\left(0.25\frac{\Sigma\left(L_{exterior}^{2} \times \Omega_{pN}\right)}{L_{adaptation} + 0.07\left(\Sigma\left(L_{window}^{2} \times w_N\right)\right)^{0.5}}\right) \tag{4.6}$$

The three parameters included in Eqn.4.6 are calculated as follows (Nazzal, 1998):

$$L_{window} = \frac{E_{v3\,shielded}}{2 f_i \times p} \tag{4.7}$$

where

L_{window}	is the average vertical luminance of the window, calculated from the reading of the sensor with the shielding pyramid [cdm^{-2}]
$E_{v3\,shielded}$	is the average vertical illuminance from the window at the sensor with the shielding pyramid [lux]
f	is the configuration factor

$$L_{adaptation} = \frac{E_{v2\,unshielded}}{p} \tag{4.8}$$

where

$L_{adaptation}$	is the average vertical luminance of the surroundings, calculated from the reading of the sensor without shielding [cdm^{-2}]
$E_{v2\,unshielded}$	is the average vertical illuminance from the surroundings at the sensor without shielding [lux]

$$L_{exterior} = \frac{E_{v1\,unshielded}}{2(p-1)} \tag{4.9}$$

where

$L_{exterior}$	is the average vertical unshielded luminance of the outdoors, calculated from the reading of the sensor without shielding [cdm^{-2}]
$E_{v1\,unshielded}$	is the average vertical illuminance from the outdoors at the sensor without shielding [lux]

The configuration factor f_I of the window from the observation place is calculated as follow (Siegel and Howell, 1972):

$$A = \frac{X}{\sqrt{1+X^2}} \qquad B = \frac{Y}{\sqrt{1+X^2}}$$

$$C = \frac{Y}{\sqrt{1+Y^2}} \qquad D = \frac{X}{\sqrt{1+Y^2}} \tag{4.10}$$

$$f_i = \frac{A\arctan B + C\arctan D}{p} \tag{4.11}$$

$$X = a / 2d$$
$$Y = b / 2d \tag{4.12}$$

where	a	is the width of the window [m]
	b	is the height of the window [m]
	d	is the distance from the observation place to the center of the window area [m]

The calculation of the solid angle and form factors can easily lead to mistakes. The apparent solid angle w_N subtended by the window, and the solid angle W_{pN} subtended of the source are here defined accurately using specific formulae (Eqn.4.13, 4.14) developed for this purpose (Nazzal, 1998).

No advice was found in the literature as to how many segments the window should be divided into when calculating ω and Ω (Aizlewood, 1998). In this research, the consistency of ω_N was tested by calculating the value for an undivided window (1.55 x 1.35 m) and for the same window divided into four segments. The w_N values were nearly identical: 0.3841 for the undivided window, and 0.3835 as a sum of the four-quarter parts (0.096 for each). The number of segments does not have any significant influence on ω_N. This suggests that the number of segments of a window is a stable part of the calculation. Thus, ω_N for a whole window is used in these calculations, as presented Eqn.4.13.

$$w_N = \frac{ab\cos(\arctan(X))\ \cos(\arctan(Y))}{d^2} \tag{4.13}$$

where

w_N is the solid angle subtended by the glare source (window) to the point of observation [sr]

And Ω_{pN} can be calculated as presented below

$$\Omega_{pN\ \mathrm{window}} = 2p\ f_i \tag{4.14}$$

Eqn.4.12 provides accurate results in comparison with existing method. See Table 4.2 for the comparison of the results from proposed solid angle calculation method and existing method. When discretizing a window into several segments, the sum of the solid angle calculated by the proposed method is much closer to 1 compared to that of the existing method.

TABLE 4.2 COMPARISON OF THE RESULTS BETWEEN PROPOSED AND EXISTING METHOD. THE CALCULATED POINT IS 1 UNIT AWAY FROM 1UNIT BY 1UNIT WINDOW.

	Hopkinson's	Nazzal's
1 piece	1.00	1.00
2 pieces	0.91	0.82
4 pieces	0.83	0.84
8 pieces	0.87	0.90

4.2.3 Measuring tools

Daylight discomfort glare is defined by a special arrangement of three illuminance sensors inside the room. Instead of using a difficult series of frequent spot luminance measurements, we used the novel monitoring methodology which calls for continuous, automatic measurement of shielded and unshielded vertical illuminances from which the window (source) luminance, adaptation luminance, and exterior luminance can be derived for the DGI_N calculation. The sensors should be spot sensors (concentrated into a spot, see Figure 4.3b). The sensors are mounted vertically on a tripod according to the midpoint of the window looking at its center (Figure 4.1). This is because the luminance distribution within the window plane is non-uniform and can therefore cause more glare than uniform light sources when positioned perpendicular to the line of sight (Waters, Mistrick and Bernecker, 1995).

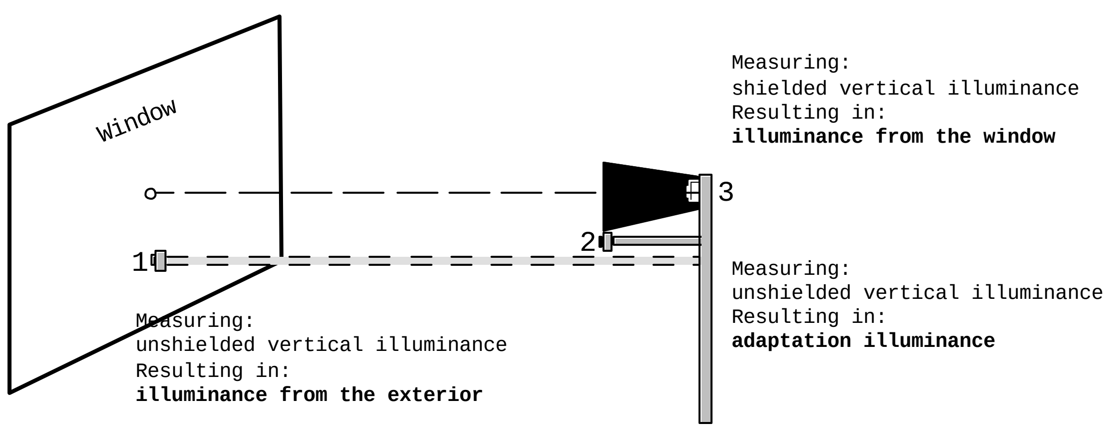


FIGURE 4.1 A SET OF THREE VERTICAL SENSORS ARE USED TO EVALUATE DISCOMFORT GLARE.

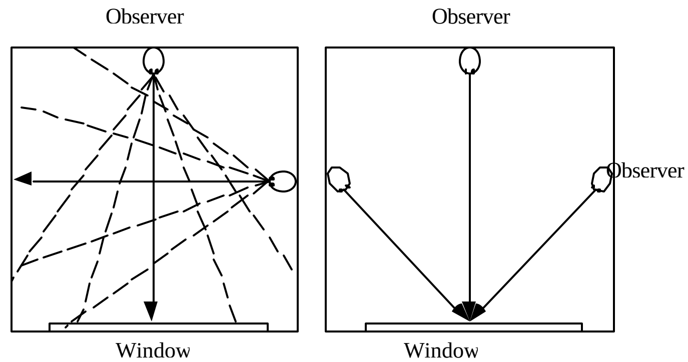


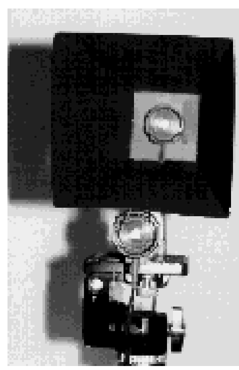
FIGURE 4.2 GLARE SENSATION IS WORST WHEN THE OBSERVER IS FACING THE WINDOW; ESPECIALLY AT 0 DEGREE FROM THE VIEWPOINT, DGI_N LEVEL APPEARS TO BE THE LARGEST.

The glare sensation is largest at 0° from the viewpoint (Figure 4.2). Here, a view facing the window is considered. The experience at the instrument position may be much worse than the seated viewing position but here the objective is to define only the worst-case condition. The calculation of DGI_N method is based on the average luminance of the window where small areas of high brightness within the overall window area are not considered. Photographs are used to record additional glare phenomena. Placing a test subject facing the window has been the practice in numerous glare researches (Chauvel, 1982 and Hopkinson, 1957).

4.2.3.1 Location of the sensors

1. The unshielded sensor Nº 1 (not necessarily mounted on a tripod but can be placed separately) is placed close to the middle point of the window at a distance of 0.20 m from the glazing (Figure 1) to measure the exterior illuminance.
2. The unshielded sensor Nº 2 is placed at the level of the opening of the shield for the sensor Nº 3 (Figure 4.3 b,c) to cover a semicircular 180° area to measure the adaptation illuminance.
3. The shielded sensor Nº 3 (Figure 4.3 a,b,c) is placed at the level of the midpoint of the window (Figure 4.1) and is adjusted with a shield, a black pyramid (with matte finish free of any reflections), to cover the rectangular window entirely without gathering light from the surroundings to measure the window (source) illuminance (Nazzal, 1998).

a. 

 **b.**

c. 

FIGURE 4.3 A THE BLACK PYRAMID TO SHIELD THE SENSOR Nº 3
B THE UNSHIELDED SENSOR Nº 2 AND THE SHIELDED SENSOR Nº 3
C THE UNSHIELDED SENSOR Nº 2 PLACED AT THE LEVEL OF THE OPENING

4.2.3.2 The distance between the window and the shielded sensor

To establish an appropriate procedure for measuring the parameters on a comparative basis under real sky conditions, subdivision of a room into three specific lighting areas--the high daylight area, medium daylight area and low daylight area, based on the effective window height, EWH, is recommended (Christoffersen and Velds, 1998). The subdivision of a room is made according to the dimensions of the window and façade, as shown in Figure 4.4. Room dimensions, however, are disregarded because the target is to define glare situation only in the vicinity of the window.

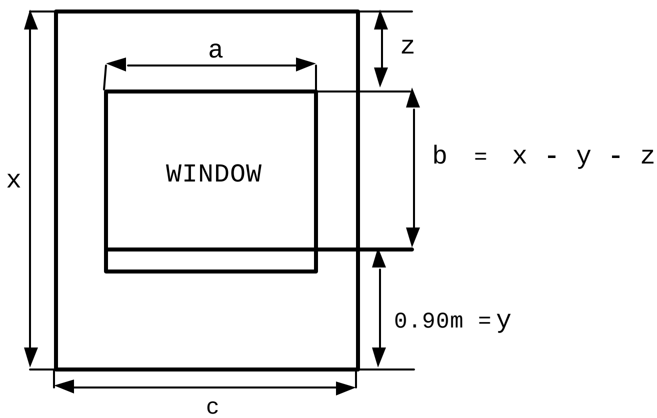


FIGURE 4.4 DETERMINATION OF EFFECTIVE WINDOW HEIGHT, EWH

The dimensions of the window and facade are then used in Eqn.4.14:

$$EWH = (ab\tau) / c \qquad (4.15)$$

where

EWH	is effective window height [m]
$ab\tau$	is effective window area [m^2]
ab	is the actual glass area above 0.9 m in the facade [m^2]
a	is the width of the window [m]
b	is the height of the window above 0.9 m [m]
τ	is the transmission of the window plane
c	is the width of the facade [m]

According to the value of EWH:

- High daylight area, where artificial light is not usually needed, starts at the facade and has a depth of approximately 2 x EWH.
- Intermediate daylight area starts at the border of the high daylight area and has a depth of approximately 1.5 x EWH.
- Low daylight area, where artificial light is usually needed, is the remaining part of the room.

The perceived degree of discomfort glare is generally lower at the back of the room than near the façade (Osterhaus, 1998). This is because the degree of discomfort glare is dependent on the sky luminance, and the sky can usually be seen only from the high and intermediate daylight areas. As the glaring sky occupies the largest part of the visual field in the high daylight area, therefore is disliked as a working place, the back edge of the intermediate daylight area was considered suitable as the position of the shielded sensor № 3.

The measurement position based on EWH is completely different from the "mid-point of the walls" standard that has been used in electric lighting. The evaluation position in the center of each wall, viewing normal to the wall, is inadequate for daylight conditions where the light distribution as a function of the distance from the window is to be determined for the needs of daylight control.

4.2.3.3 Geometric description of the shield

When the window dimensions are known and the distance between the window and the shielded sensor has thereby been determined, it is possible to shape the pyramid according to that information (Figure 4.5). The shape of the shield, however, can also be different from a pyramid (e.g. a cube), provided that the sensor is totally covered by the shield and can "see" only the window. The inner surface of the shield is black and free of any reflections. The shape of the opening of the shield, and the distance between the opening and the shielded sensor, are essential and are derived from Eqn.4.15, 16. Thus this distance can be calculated according to Eqn.4.17 and the dimensions of the shield opening according to Eqn.4.18.

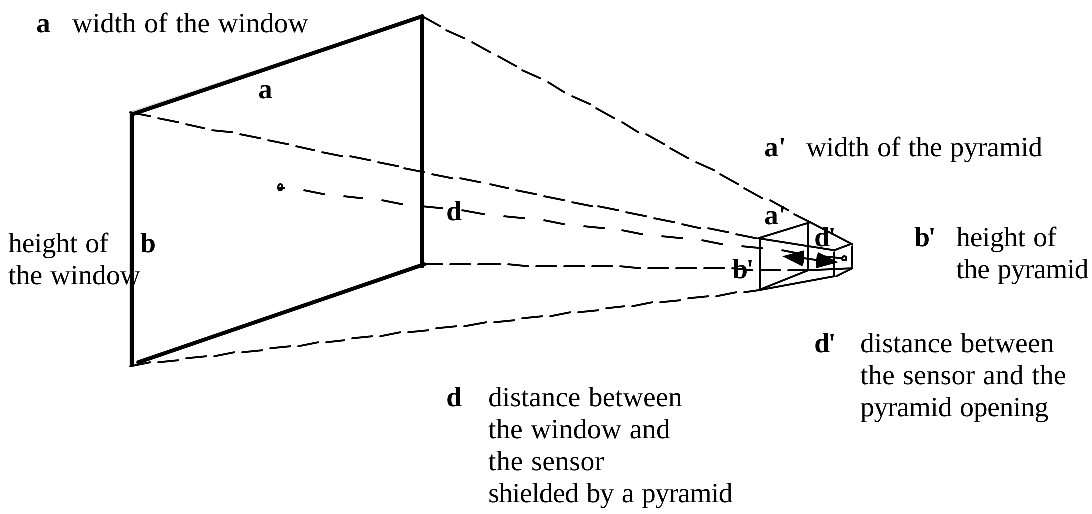


Figure 4.5 Similarity of triangles is the base for shaping the opening of the pyramid (Nazzal, 1998)

It is supposed that the sensor shielded by the pyramid is concentrated into a spot:

$$\frac{a}{2d} = \tan a = \frac{a'}{2d'} \qquad \frac{b}{2d} = \tan b = \frac{b'}{2d'} \tag{4.16}$$

$$\frac{a'}{a} = \frac{d'}{d} = \frac{b'}{b} \tag{4.17}$$

Thus the distance between the opening and the shielded sensor can be calculated:

$$d' = \frac{db'}{b} \tag{4.18}$$

and the dimensions of the shield opening can be calculated:

$$a' = \frac{ad'}{d} \qquad b' = \frac{bd'}{d} \tag{4.19}$$

where

a	is width of the window [m]
a’	is width of the pyramid [m]
b	is height of the window [m]

b’	is height of the pyramid [m]
d	is distance between the window and the shielded sensor [m]
d’	is distance between the sensor and the pyramid opening [m]

4.3 Testing the applicability of the method

The goal of this section was to determine how closely the DGI_N method and the existing DGI proposed by Chauvel are correlated. The experimental conditions were simulated by the Radiance program. The room configurations presented below were modelled and simulated (Figure 4.6, 4.7, 4.8). The viewing point was located at sensor № 3 looking at the midpoint of the window. The field of view was an angle of 70 degrees measured in a horizontal plane perpendicular to the line of sight.

Locations	Helsinki, Finland and Fort Worth, TX
Sky	Clear and overcast
Room	3.7m x 2.7m x 2.68m, located on the third floor (6m from ground)
	Ground is covered by green grass with the reflectance of 0.12
	Ceiling - reflectance 0.70
	Walls - reflectance 0.65
	Floor - reflectance 0.30
Window	South facing with no obstructions, 1.55m x 1.35m
	75 % transmittance (for visible light) for double clear glazing

1. Vertical illuminance at 0.20 m off the window (interior)
2. Vertical illuminance at 1.93m off the center of the window 1.50m above the floor
3. Vertical illuminance at 2.10m off the center of the window 1.58m above the floor with a shield (pyramid).

Exact dimensions of the test room and thus the basis of determination of the distance (d) between the shielded sensor № 3 and the window, as well as the shape of the shield, are shown in Figure 4.6. According to the above information:

$$EWH = (1.55m \times 1.35m \times 0.75) : 2.66m = 0.59m \approx 0.60m.$$

Therefore, the high daylight area has a depth of 1.20m and the intermediate daylight area has a depth of 0.90m.

Thus the correct distance (d) between the shielded sensor and the window is at the back edge of the intermediate daylight area:

$$1.20m + 0.90m = 2.10m \text{ (Figure 4.6)}$$

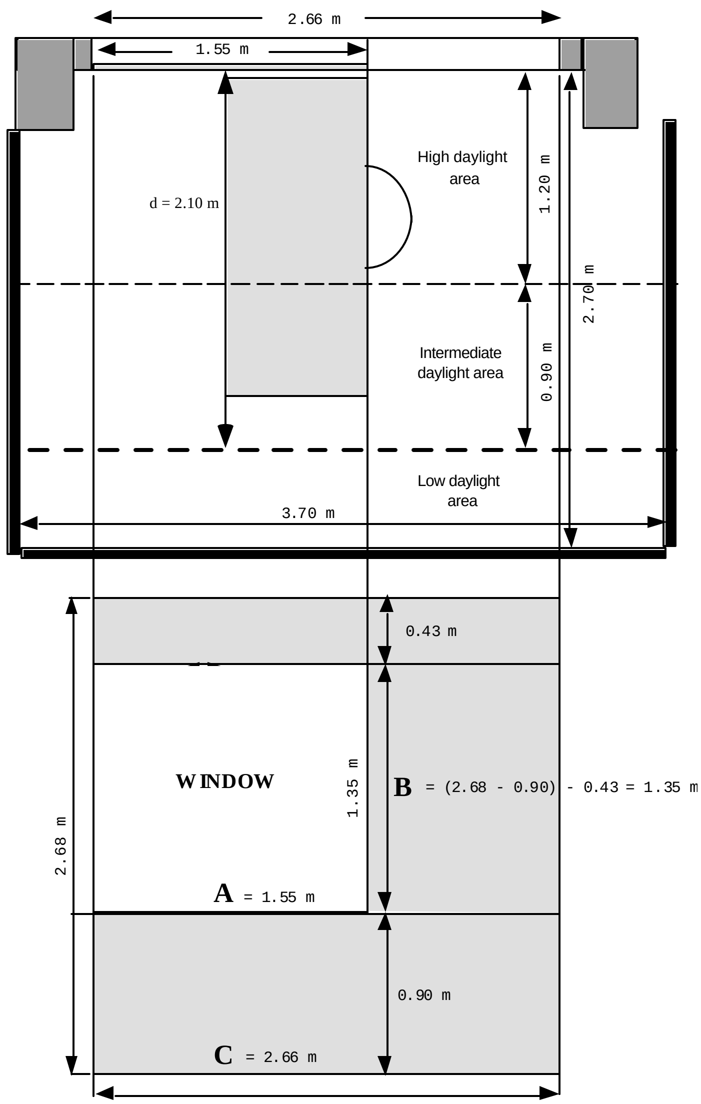


FIGURE 4.6 DIMENSIONS OF THE TEST ROOM

The midpoint of the window, and thus the level of the sensor № 3, is at a height of 1.58m. The distance between the shield opening and the sensor inside was chosen to be 0.17m. Thus the dimensions of the opening are, according to Eqn.4.18 (Figure 4.7):

$$a' = \frac{ad'}{d} = \frac{1.55\text{m} \times 0.17\text{m}}{2.10\text{m}} = 0.12\text{m} \qquad b' = \frac{bd'}{d} = \frac{1.35\text{m} \times 0.17\text{m}}{2.10\text{m}} = 0.11\text{m}$$

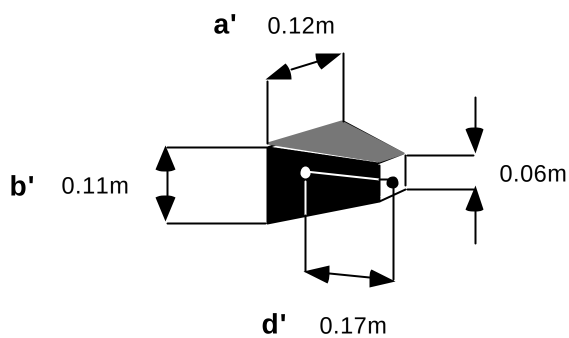


FIGURE 4.7 THE DIMENSIONS OF THE SHIELD

The Radiance program simulating the experimental conditions was used to provide luminance values required for the new glare calculations. A Radiance script was written to calculate the luminance values for the whole year in clear sky conditions, including direct sunlight onto the measurement point. In order to simplify the study, the simulations were calculated for every month at 10 day intervals (day 10, 20,and 30) and every hour from 10.00 a.m. to 3.00 p.m. Once Radiance finished generating the required luminance values, the DGI_N values were computed. The existing glare index values were derived by the glare utility program in Radiance.

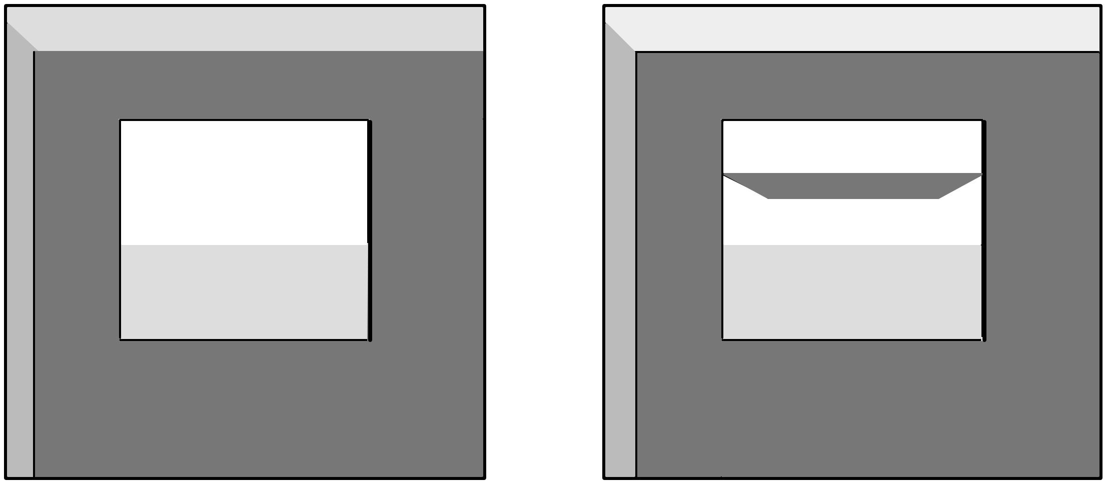


FIGURE 4.8 A VIEW OF THE SIMULATED TEST ROOM WITHOUT AND WITH A LIGHT SHELF

Finally simulations of the room with another daylighting control strategy, the light shelf, were explored in the circumstances of Helsinki using the DGI_N method (Figure 4.8). Light shelves are horizontal solid fixtures positioned at right angles to either exterior or interior of both windows. An external shelf with length of 1.55m and depth of 1.20m at 1.90m above the floor level was used here in the model room identical to the previous one (Figure 4.8). The upper and lower surfaces of the shelf were painted with white material of 70% reflectance. The window glazing was clear with 75% transmittance.

4.4 Results

4.4.1 Comparison between the two systems

Figure 4.9 shows that the glare derived from the DGI_N method is higher than that of Chauvel's since the weight of the average luminance in Chauvel's method is higher than it is supposed to be. That makes the calculated glare in that method lower than normal. The two procedures differ significantly in how different light sources and solid angles impact the total glare condition. It can be seen that the DGI_N method provides more reasonable results; the higher source luminance provides more glare sensation. The variation with vertical illuminances was found even larger in the simulations run for the circumstances of Texas as presented in Figure 4.10. It seems, according to the ongoing simulations, that as the window becomes larger, the glare will increase (co-variance) but not to the extent predicted. This is because the glare source occupying a large part of the visual field, which increases the adaptation luminance, thus balancing out the effect of window size. This phenomenon can be seen in Figure 4.9 that shows scattering of the DGI_n. This is because when there is the direct sunlight falling on $L_{adaptation}$ sensor or the unshielded sensor Nº 2, the adaptation luminance increases and the DGI_n decreases. The glare index of Chauvel behaves the opposite. Moreover, there is plenty of scatter in the DGI values; for example, vertical illuminance of 39000 lux can result in the DGI value of 2 as well as 25, which does not make a good sense.

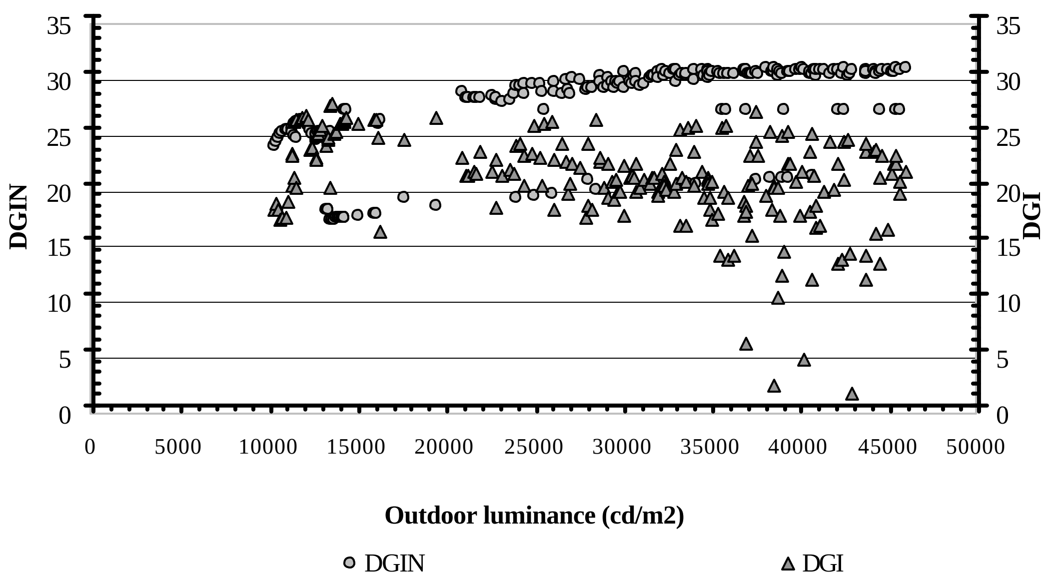


FIGURE 4.9 THE DGI_N AND THE DGI OF CHAUVEL WITH CLEAR GLASS AS FUNCTION OF THE VERTICAL OUTDOOR LUMINANCE IN HELSINKI, FINLAND.

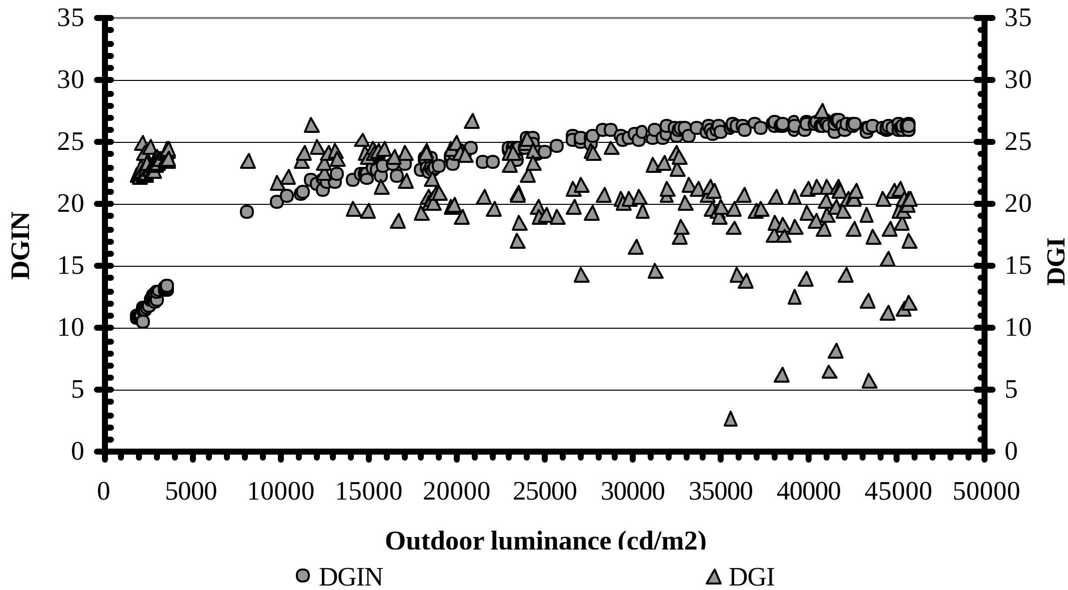


FIGURE 4.10 THE DGI_N AND THE DGI OF CHAUVEL WITH CLEAR GLASS AS FUNCTION OF THE VERTICAL OUTDOOR LUMINANCE IN FORT WORTH, TEXAS

Typical for the variation of the exterior vertical illuminance in Helsinki (Figure 4.11) is that the greatest values occur in spring and autumn while the smallest values are found in winter. In Fort Worth, Texas (Figure 4.12), the greatest values are found in winter whereas the smallest values occur in summer. The obvious explanation for the difference is the higher solar angle of Texas throughout the year.

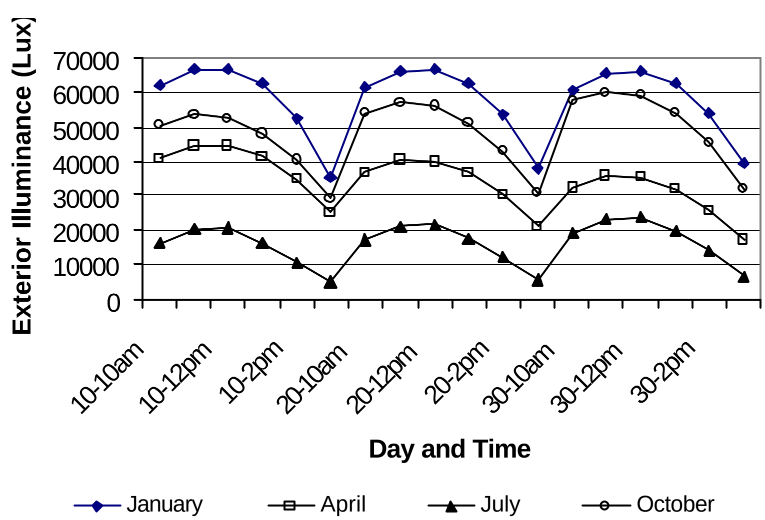


FIGURE 4.11 THE VARIATION OF THE EXTERIOR VERTICAL ILLUMINANCE IN HELSINKI FROM 10 A.M. TO 3 P.M. ON THE 10TH, 20TH AND 30TH OF JANUARY, APRIL, JULY AND OCTOBER.

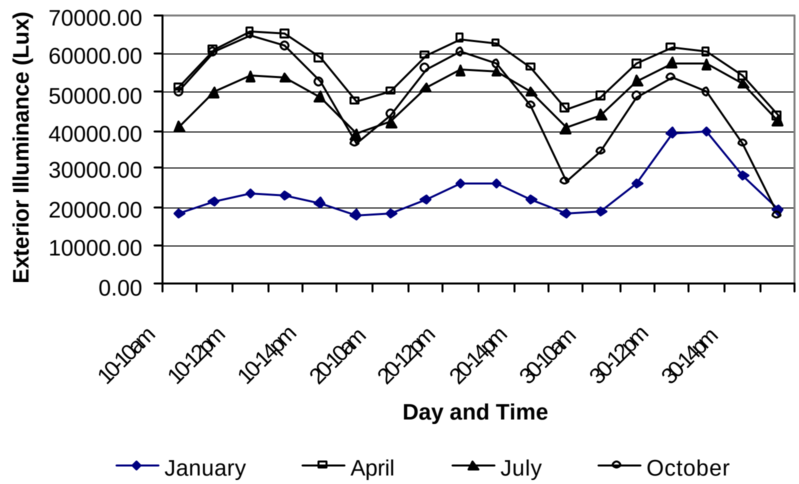


FIGURE 4.12 THE VARIATION OF THE EXTERIOR VERTICAL ILLUMINANCE IN FORT WORTH, TEXAS, FROM 10 A.M. TO 3 P.M. ON THE 10TH, 20TH AND 30TH OF JANUARY, APRIL, JULY AND OCTOBER.

The results of calculated glare for the whole year in Helsinki are shown in Figure 13 and 14. The smallest glare index values of the new method (Figure 4.13) occur in winter from the middle of October to the middle of February. This is because in Helsinki, both the lowest solar angle and the smallest vertical illuminance values on the window occur in winter. The divergence between the different hours in winter can be explained by reflections; the DGI_N values are smaller at noon and 1 p.m. than at 10 and 11 a.m. or 2 and 3 p.m. The greatest glare index values occur between spring and autumn because of a greater solar angle and greater vertical illuminance at that time of year. The higher the source luminance, the worse the glare sensation is according to the new method. The glare index of Chauvel (Figure 4.14) behaves the opposite, giving the smallest values at the end of April and at the end of August so that the greatest glare index values occur in December – January at the time of the smallest solar angle and the smallest vertical illuminance.

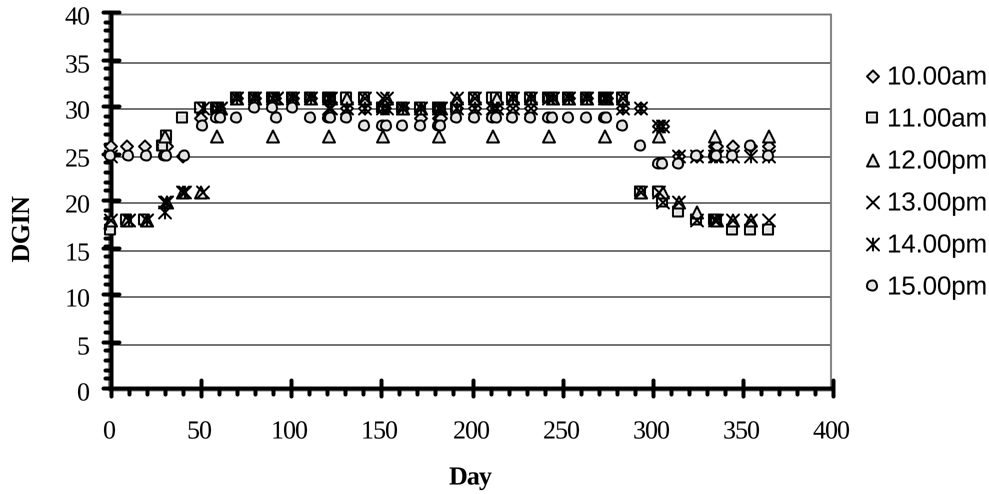


FIGURE 4.13 THE DGI$_N$ WITH CLEAR GLASS CALCULATED FOR THE WHOLE YEAR IN HELSINKI

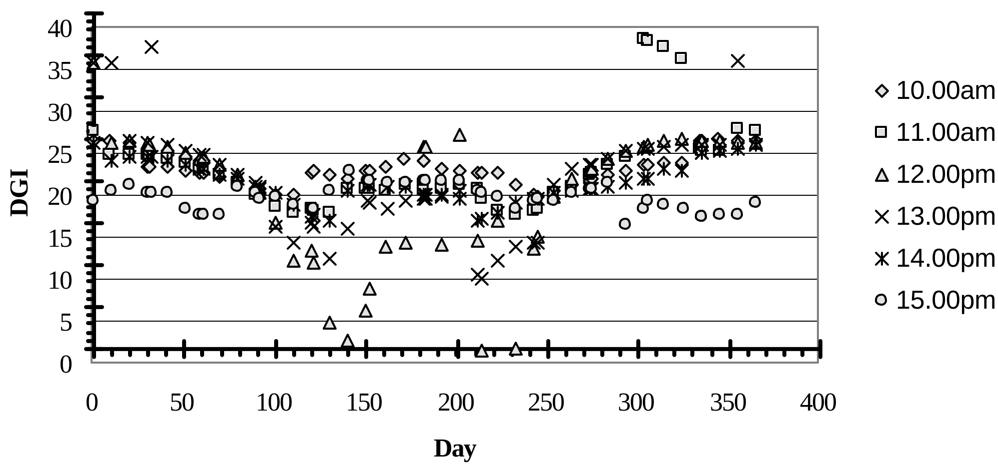


FIGURE 4.14 THE DGI OF CHAUVEL WITH CLEAR GLASS CALCULATED IN HELSINKI.

4.4.2 Light shelf calculations

Under clear skies, the light shelf reduces illuminance up to 90% within the place near the window. The least reduction occurs in the back of the room. On sunny days in spring and summer, the illuminance in the back of the room reduces by 0-18%. Regarding the graph shown in Figure 4.15, glare levels reduced significantly in spring and summer since the light shelf provides shade that prevents direct sunlight from penetrating into the room. The available daylight is more uniformly spread, improving visual conditions within the space, especially near the window. During the winter months (from the middle of November to the end of January), the glare levels for the room with a light shelf are still high and remain the same as that of the room without a light shelf. This is because the sun angle is low in the winter months at northern latitudes so that the light shelf is not very effective. However, the DGI_N appears small also in wintertime at certain times of day (11 a.m. and 2 p.m.); at noon (12 and 1 p.m.) sunrays come in without any impediment, and that is the case also early in the morning before 10 a.m. and late in the afternoon after 3 p.m. At 11 a.m. and 2 p.m. the sunrays hit the underside of the light shelf at such an angle that the rays are reflected into the room to balance out the glare effect. The reason for some negative values in the graph (Figure 4.15) is that sensor Nº 1 ($L_{exterior}$) was shaded by the light shelf while sensor Nº 2 ($L_{adaptation}$) and 3 (L_{window}) were exposed to direct sunlight at certain times of the year. Since the value of the nominator is less than the denominator when applied to Eqn.4.6, the result becomes negative.

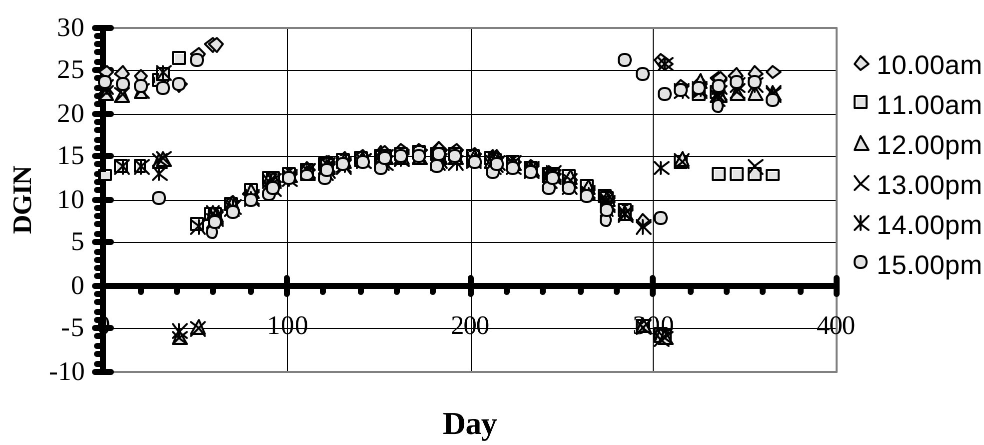


FIGURE 4.15 THE DGI_N WITH A LIGHT SHELF CALCULATED FOR THE WHOLE YEAR

The proper DGI evaluation would represent eye perception in which the eye perceives light in a logarithmic scale. The calculated exterior luminance, which has more effect on glare perception, is plotted in Figure 4.16 a and b into a logarithmic scale for the whole year with and without the light shelf. The graph presents results very close to the DGI_N prediction.

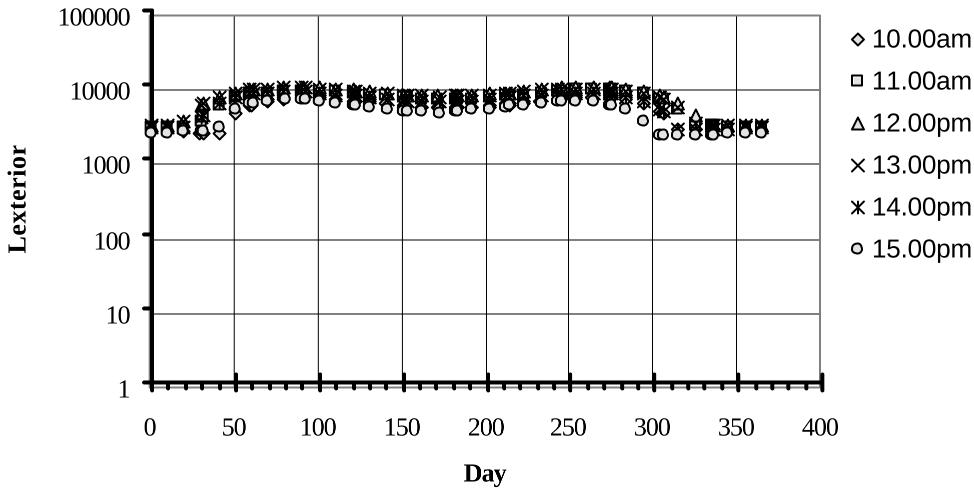


FIGURE 4.16A L EXTERIOR WITHOUT LIGHT SHELF CALCULATED FOR THE WHOLE YEAR

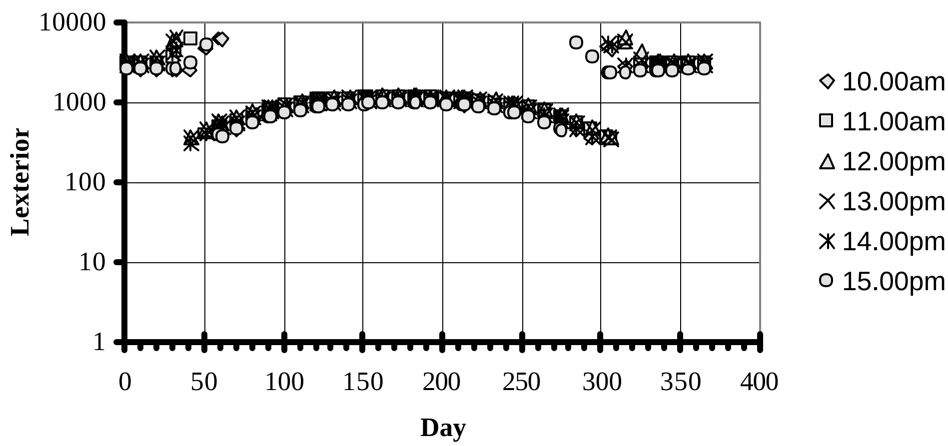


FIGURE 4.16B L EXTERIOR WITH LIGHT SHELF CALCULATED FOR THE WHOLE YEAR

4.5 Subjective experiment conducted in a typical workplace environment

The purpose of the experiment is to see how the results from new DGIn method and from the subjective experiment are correlated. Three illuminance levels were recorded. The test subject must have the same position with the measuring equipment, according to the calculated DGIn such that the results from the mathematical calculation and the subjective assessment are comparable. Subjects were asked to perform usual task on computer and to justify the glare and lighting condition within the space. More detail on the experiment can be found in Appendix C.

4.5.1 Space and lighting conditions

Locations	A software design workplace, Toronto, Canada
Sky	Clear, partly cloudy, and overcast.
Room	3.71m x 2.92m x 2.70m, located on the second floor
	Ground is covered by green grass with the reflectance of about 0.12 and parking lot with the reflectance of about 30%
	Ceiling - reflectance 0.70
	Walls - reflectance 0.50
	Floor - reflectance 0.30
Window	East facing windows with no obstructions, 38 % transmittance

4.5.2 Procedures

There were 29 subjects aging between 20-60 years old. Subjects were interviewed for 7 minutes, which allowed enough time for eye adaptation. Subjects were then asked to perform a task (questionnaire) on a computer. Sitting positions were randomly side and front facing window. Questions included glare perception and evaluation. During the experiment, illuminance and luminance values were measured with respect to the new DGI method. Measuring equipment were Sekonic Dual Spot F L-778 Luminance meter and Gossen Color-Pro illuminance meter.

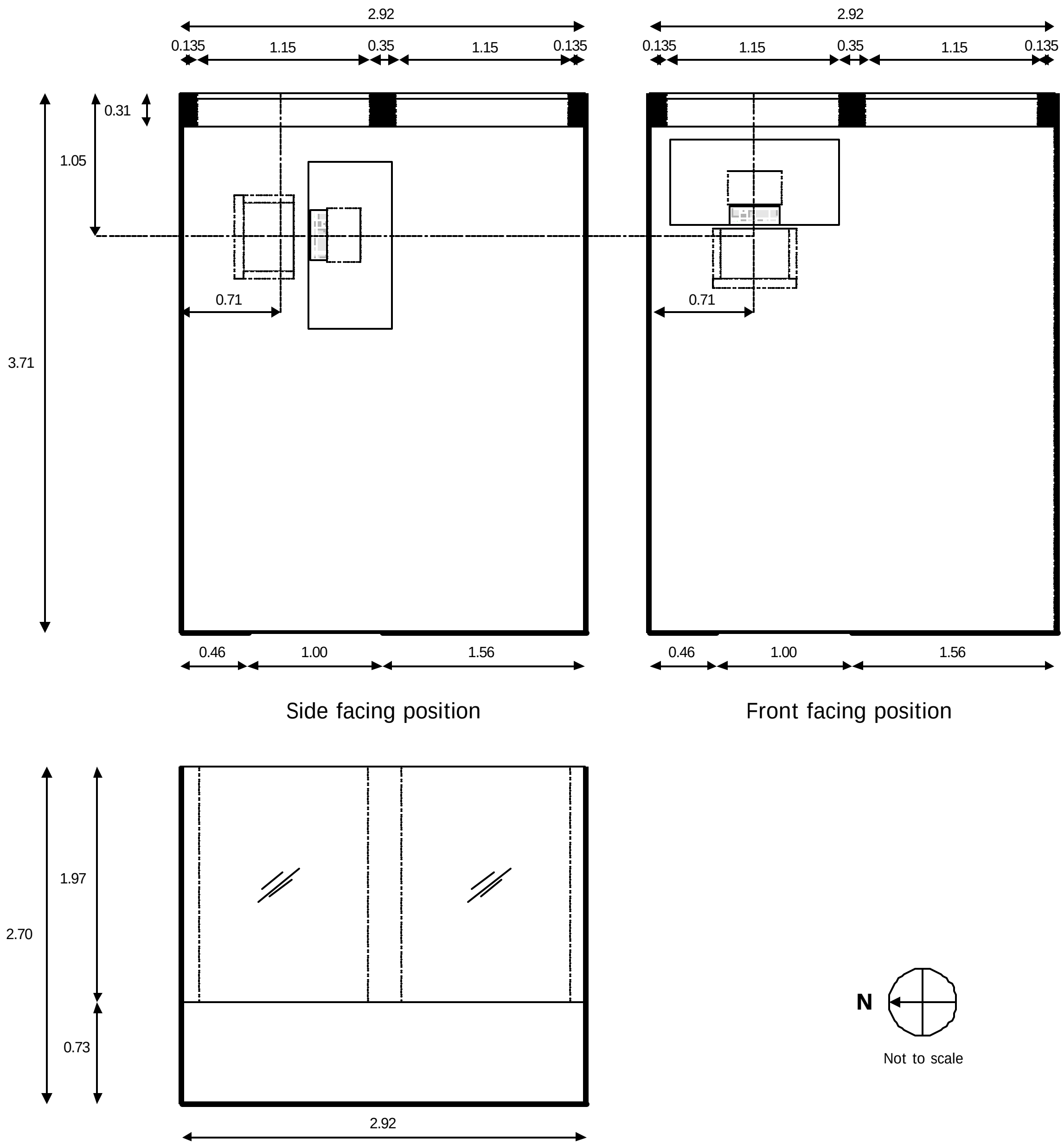


FIGURE 4.17 PLAN AND SECTION OF THE SELECTED SPACE FOR THE EXPERIMENT

FIGURE 4.18 SUBJECT POSITIONS AND EQUIPMENT SETTINGS

4.5.3 Results

The data from the experiment has been analyzed by Minitab version 12. Comparisons of the correlation between subjective response to glare perception and the Daylighting Glare Index are summarized below. Appendix D describes procedures, numerical results and analysis in detail.

TABLE 4.3 RESULTS FROM THE SUBJECTIVE RESPONSE

	Pearson Correlation of the subjective experiment	
	Existing DGI	New DGI
Clear Sky		
Front facing position	-0.72	-0.30
Side facing position	0.43	0.41
Overcast Sky		
Front facing position	-0.52	-0.23
Side facing position	0.61	0.68

The sign of the correlation coefficient defines the direction of the relationship, either positive or negative. A positive correlation coefficient means that as the value of discomfort glare perception increases, the value of the other predicted value increases; as one decreases the other decreases. On the other hand, a negative correlation coefficient indicates that as one variable increases, the other decreases. This phenomenon appears in the front facing position for both sky conditions which it should exhibit positive values. It implies that factors affected glare perception could be context outside the windows, parking lot, and reflections from cars and adjacent buildings, in addition to luminance of the windows and exterior. A correlation coefficient of 0.68 (DGI_n) indicates a stronger degree of linear relationship than one of 0.61 (DGI). However, this experiment is based on only 29 subjects under all sky conditions and all positions. When the data has been analyzed and categorized into different sky conditions, more subjects are required in order to accurately evaluate the correlations. Therefore, it can be concluded that there is a need to explore and investigate more on discomfort glare from natural light source.

4.6 Conclusion

The author suggests that discomfort glare from daylight could be predicted mathematically. Objective glare evaluation is an essential prerequisite for user comfort in modern buildings with innovative daylighting systems and daylight responsive lighting controls. The only reliable data for lighting control can be derived from the DGI, not from variable subjective assessments, but there is a need for a more accurate DGI. The change from the obsolete Hopkinson's formula through Chauvel's formula to the proposed formula is a great improvement.

The DGI_N method appears to yield sensible and consistent glare values even in direct sunlight. These are invaluable in the assessment of daylight system performance. The DGI_N will grow along with the increase in solar angle or vertical illuminance on the window, which is very reasonable, whereas the DGI of Chauvel behaves just the opposite: the higher the solar angle or the vertical illuminance, the smaller the glare sensation. Obviously the method of Chauvel reacts first of all to the existence of the sun down close to the horizon and thereby to the sunrays entering the room, while the new method is sensitive to the growing vertical illuminance and thereby to the source luminance. This is in harmony with Osterhaus's observation that the best correlation with perceived degree of discomfort glare was found for the vertical illuminance or the overall brightness in the visual field. Moreover, scatter of the DGI values of Chauvel is very large. There is a conflict on the assumption made on Chauvel's method and the implementation in Radiance where Radiance takes effects of the direct sunlight into the calculation process.

The DGI_N method may have future applications in lighting control systems. The measurements will not cause problems since glare is determined based only on three illuminance values, and measuring the exterior illuminance is already included in the control systems. Daylight responsive lighting controls that react also to glare, by using a new glare algorithm based on the proposed new method, will improve visual comfort.

The new method was developed with the hope that architects and lighting designers would adopt it as the method for the assessment of daylight system performance. This could make the design and selection of daylighting systems and lighting controls easier. This method is incorporated into this research as a part of daylighting studies. Although, this method had been compared to subjective experiment and yielded promising results, it had been conducted on a small number of subjects. Further study on this issued could be done in the future.

Note: Figure 4.1 to 4.16 presented in this chapter are parts of a paper written by the author and Nazzal presented at the IESNA Annual Conference 2000.

Chapter V: Daylighting Design Tools and Vision

To clearly establish practical need, this chapter first analyzes the general nature of lighting design and analysis tools. While there is wide divergence in the approaches of different designers and methods, there appear to be common needs that could effectively be met by the application of the latest computational technology—particularly in problem-solving process areas. This part of the chapter reports and surveys existing design and analysis tools and software related to the subject of lighting. Then, recommendations in this section include suggestions or goals to fill the critical gap between available software processing and actual needs. I believe that to accomplish the goals, it is necessary to take an interdisciplinary approach, incorporating the fields of art and technology, together with established knowledge in design. Therefore, the next section introduces an inverse method or an optimization method using a genetic algorithm in the design process.

5.1 Lighting Design Tools

This thesis surveys existing design tools related to the subject of lighting. There is a tremendous amount of software available, but these programs do not generate design and creativity. Rather, they analyze existing design schemes. Lighting software was selected for review, and the selection included both broadly-applicable and narrowly-defined analysis programs. It was found that these programs are better suited for rendering and analysis purposes rather than assisting in design. In fact, most programs require existing building geometry design as input for lighting performance results; they have no capacity to generate design creativity and knowledge during the design process.

5.1.1 Computer Software

There is a fair amount of software available, but these programs do not address all users' needs. After an initial screening process, only selected programs were reviewed. Although several programs are quick and easy to use, they present a number of limitations for learning and designing. In contrast, other more robust and comprehensive programs that are more time consuming to learn and apply are useful for rendering and/or research purposes.

5.1.1.1 ADELINE

ADELINE (Advanced Day- and Electric- Lighting Integrated New Environment) is a lighting design software that has the capacity to calculate daylighting, electric lighting, and whole building analysis. It provides 3-D CAD modeling of a space; automatically generates SuperLite and Radiance input files; calculates interior illuminance levels in complex building spaces; and graphically displays analysis results predicting the dynamic, thermal, and energetic performance of a building. The simulation process is still a direct process that involves massive computations. Geometry and surface characteristic codes are inputted using 3-D CAD; and analysis runtime parameters (e.g., geographic location, time of year, sky conditions) are entered via graphic user interface dialog boxes. It requires significant amount of detailed information about the building and its context. Moreover, the output generates various graphic displays of interior illuminance levels, including 3-D renderings, and also preformatted text files containing detailed analysis results that are sometimes hard to interpret.

5.1.1.2 Lightscape

Lightscape is a lighting calculation software using both radiosity and ray tracing techniques. Radiosity algorithms used for rendering and calculating cannot deal with specular and transparency effects. Besides, there is an error in material reflectance that could decrease the mean measured illuminance level by 15% (Ashmore and Richens, 2001). The true sky distribution is not considered and no ground component is included. The sky distribution is considered diffuse upon striking the window, but only appears to send light downward. Lightscape has the potential to be a very good daylight modeling system if the developers upgrade the way in which the sky and ground are considered.

5.1.1.3 Radiance

Radiance is a powerful ray-tracing program that enables the user to obtain accurate and physically valid lighting and daylighting simulations. The flexibility of an open source program and the capacity to quickly present the realistic picture make Radiance the most advanced design tool for daylighting study. Typically, the purpose of daylighting study would be to determine and explore the sun-path in the space where speed is of more concern than accuracy. However, when emphasis is placed on quantification of the lighting/daylighting, many parameters controlling the ray-tracing algorithm must be carefully adjusted.

Radiance Algorithm:

Radiance simulates light propagation using a ray-tracing approximation technique. For reasons of economy, the ray-tracing approach to rendering follows “view rays” from the virtual focus of an eye or camera through pixels in an imaginary image plane into the environment. To obtain a balance between speed and accuracy, the hybrid deterministic/stochastic technique is the core of computation in Radiance. The direct component is computed with rays traced to random locations on the light sources. The specular indirect component is computed with rays distributed about the mirror and transmitted directions, using uniformly weighted Monte Carlo sampling. Once these two components are removed from the integral, the diffusely interreflected component is computed by occasional evaluation of the simplified integral at dynamically selected locations.

Radiance Operation

1. Scene geometry
2. Surface materials
3. Lighting simulation and rendering

Scene Geometry

Scene geometry is modeled using “boundary representation” or B-rep of three basic surface classes: 1. Polygon (an *n*-sided planar polygon); 2. Sphere; and 3. Cone. When the geometry has been defined in one or more scene files, this information is compiled into an octree using the oconv command.

Surface Materials

There are 25 material types and 12 other modifier types to choose from the Radiance library. Radiance pays careful attention to materials that determine how light interacts with the geometry. Some of the most frequent materials are light, illum, plastic, metal, dielectric, trans and BRTDfunc. Below is the basic format used to define material in Radiance.

```
# modifier TYPE identifier
# number_string_arguments [string arguments...]
```

number_integer_arguments [integer arguments...]
number_real_arguments [real arguments...]
#

The special modifier "void" means no modifier. TYPE is one of a finite number of predefined types. The meaning of the arguments following is determined by this type. (See Radiance Reference Manual for details.) The identifier may be used as a modifier later. All values are separated by white space (spaces, tabs, new lines). See below for examples of material specified in Radiance text format.

Plastic is probably the most frequently used material in Radiance. A typical Radiance text format is as follows.

```
void plastic gray75
0
0
5       .75     .75     .75     0       0
# 5     R       G       B       specularity     roughness
```

In order to calculate the reflectance from the parameters of plastic above, the following formula needs to be computed.

Reflectance from Plastic = (.263*RED + .55*GREEN + .082*BLUE) * (1-Specularity) + Specularity

Also, the formula for metal material can be computed based on:

Reflectance from Metal = (.263*RED + .55*GREEN + .082*BLUE)

An optimized reflectance can be obtained by using multipliers for Red, Green, and Blue in the above equations in order to maintain original color appearance. For a translucent material such as fabric or membrane, the following format is applied. See Radiance email archives for more detail at http://radsite.lbl.gov/radiance.

```
void trans fabric
0
0
7     .3    .3    .3    0             0            0.6     0.1
# 7   R     G     B     specularity   roughness    trans   tspec
```

Diffuse transmittance = AverageRED,GREEN,BLUE*trans*(1-tspec)

Specular transmittance = AverageRED,GREEN,BLUE*trans*tspec

Diffuse reflectance = AverageRED,GREEN,BLUE*(1-trans)

The translucent material specified above as fabric would have 12% diffuse reflectance ((1-0.6*0.3), 16.2% diffuse transmittance (0.3*0.6*(1-0.1)), and 1.8% specular transmittance (0.3*0.6*0.1). The average RED, GREEN, and BLUE or its gray value can be calculated as stated in the following formula.

AverageRED,GREEN,BLUE = 0.265*RED + 0.670*GREEN + 0.065*BLUE

Lighting Simulation and rendering

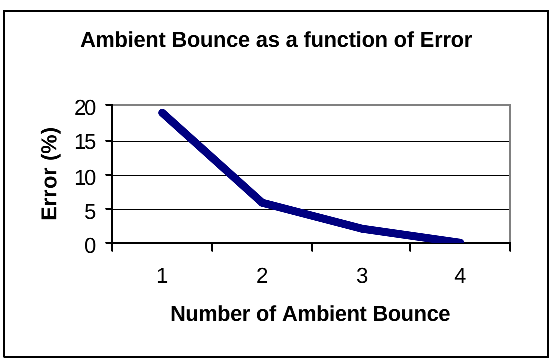
The backward ray-tracing method in Radiance is generally more efficient and gives mathematically the equivalent of the following light forward process. However, the difficulty with backward ray tracing is an incomplete model of light interaction. Radiance overcomes this shortcoming with an efficient algorithm for computing and caching indirect irradiance values over surfaces, while also providing more accurate and realistic light sources and surface materials. The main rendering programs in Radiance are rview, rpict, and rtrace. Typically, rtrace will return irradiance at a given point and normal to surface in the scene. To convert the energy in watts/m^2 out of rtrace for red, green, and blue to illuminance in lux, the following formula needs to be applied.

Lux = (0.265*RED + 0.670*GREEN + 0.065*BLUE)*179

Speed and Accuracy

Radiance is a flexible tool such that it allows the user to adjust parameters that affect the quality and speed of rendering and calculation. Numbers of simulations were conducted. It was found that –ab option or ambient bounces option is the most expensive. Recommended setting –ab option is two, which yields a reasonably accurate and calculation. Other recommended options can be found in Radiance site. Below is the relationship found between speed and accuracy tested on a Silicon Graphics Indigo machine for the problem stated in Chapter 8, part 8.3. GA parameters used were: population size of 10, number of generation of 35, crossover rate of 0.9, and mutation rate of 0.001. The mutation rate is the recommended value found in IEEE Transactions on Evolutionary Computation (Back, Hammel, and Schwefel, 1997).

Ambient Bounce	Error (%)	Time to evolve (Min)
1	19	8
2	6	30
3	2	155
4	0	



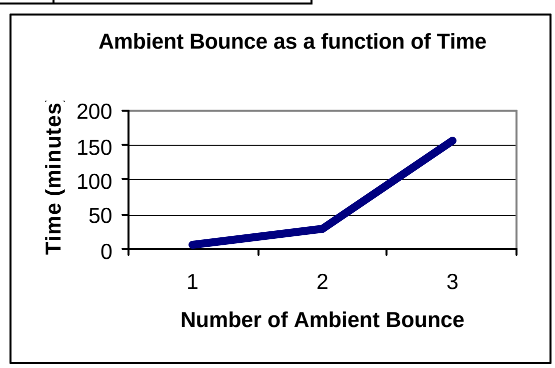


FIGURE 5.1 RELATIONSHIP BETWEEN SPEED AND ACCURACY IN RADIANCE

5.1.2 Validation of lighting simulation program under real sky conditions

A comparison between the output of Lumen Micro (discrete radiative flux transfer), Radiance (Monte Carlo backward ray tracing) and measurements from a full scale model was conducted by Houser in 1996. He found that Radiance is the most accurate program. More accurate output requires a longer time period for computation. This conclusion is in agreement with Mahdavi's research comparing Lumen Micro, Superlite, and Radiance. Another comparison between real world measurement and synthetic images generated with Radiance was conducted by Ward in order to validate Radiance. Therefore, Radiance has been chosen for this study for the following reasons:

1. It's a physically based lighting program to allow accurate calculation of luminance/illuminance;
2. It has a capability to model complex geometry;
3. It supports a wide variety of reflection and transmission models;
4. It can link scene description input and output to CAD programs;
5. The program is open for any user.

A major drawback of these existing building simulation tools is that they were not designed for use by building designers. They lack an easy and friendly mechanism for entering input data and reviewing output. Their use typically requires a steep and prolonged learning curve. Even after such a significant investment, each subsequent use of such simulation programs requires time-consuming preparation of "input files," or descriptions of the building and context. In addition, the produced "output files" are typically in the form of alphanumeric tables, which are difficult to review and interpret. In this context, digital simulation allows the designer to achieve an optimum solution via a process of trial and error.

5.2 Vision on a New Lighting Design Tool

A design tool should not be just a computer-aided drafting tool or computer-aided analysis tool. It should be a learning tool as well as a design tool in which the context and creativity should be established by the designer. Then the designs of solutions could be automated using optimization techniques and/or artificial intelligence techniques. Regarding traditional design process, each design that the designer works on adds to the experience and knowledge of the designer. In this circumstance, the designer learns from each design.

With this concept in mind, a design tool should be useful to the designer such that he or she could gain information experience and knowledge during the design process. Moreover, information and solutions derived from the tool could be used for improving the quality of design and knowledge for the next time that the system is used to solve a similar problem. For instance, lighting solutions from existing projects can be categorized for specific context, and could be added on to a visual database of lighting for use as reference. The designer can use this information for the next project, which the system would use less amount of time to evolve such solutions based on a better initial guess. This means that the tool should have the capacity to recognize appropriate problems. Furthermore, when one understands what is going on in the design process, the tool should be able to help one built ones' own intellectual methods or signature. In other words, the effect of this could be to personalize the tool for each user.

In term of lighting design, we know that good physical models can illustrate the interrelation between natural light and the built environment. Imagery created by computers should also maintain a quality of light. Renderings created by Radiance can be adjusted to provide a good quality of light as well as a sense of depth and texture, which are the important aspects in human visual perception. Besides, it is useful in describing the true interaction of light within a space. Beyond the effect of light and how it is distributed within a space, the design tool should inform the designer of the performance as well as a potential of good design solutions. The knowledge can be derived from knowing the relationship between design and lighting performance variables as well as context variables.

In the next chapter, the use of optimization technique and recommendations include how a new tool might better fit into design and knowledge creation in general. The information and available technology are developed and implemented into the new design tool. The tool attempts to improve the design process and is concerned with the improving the learning.

Chapter VI: A New Approach and Search Method

As aforementioned, what the architect or designer needs is the best solution for a particular set of goals. Optimization models search the whole field of feasible solutions to identify the best building geometry solution, producing designs that are quite impossible to achieve in any other way (Radford, 1988). Thus optimization directly approaches an answer to the designer's fundamental question of what is the "best" solution. However, the disadvantage is the difficulty of formulating meaningful quantifiable objectives. Most architectural problems typically involve variables that are discrete and discontinuous, and relationships that are nonlinear. This section will discuss types of optimization used in architectural design: classical calculus, linear programming, nonlinear programming, and dynamic programming as well as a new approach using a Genetic Algorithm in lighting design.

6.1 Architectural problems

Most architectural problems typically involve variables that are discrete and discontinuous, and relationships that are nonlinear. However, optimization problems using calculus-based methods are expensive over time, when the problem size grows or when additional constraints are added, because they require the existence of derivatives. Moreover, they can only find local optima.

Figure 6.1, below, is a result from an exhaustive test, illustrating a solution space for finding the best lightshelf depth and height for a south-facing window. An objective is to achieve the desired lighting level of 50 footcandles at 3 different points in a room: front, center, and back. The room and window dimensions were kept static. The only variables are lightshelf depth and height, ranging from 3' to 5.5' at discrete steps of 0.5', and 6.3' to 7.5' at discrete steps of 0.3', for depth and height respectively. The lower the rating score, the better the solution. More than one local minimum and a global minimum derive from the above results. Thus a global searching method is needed.

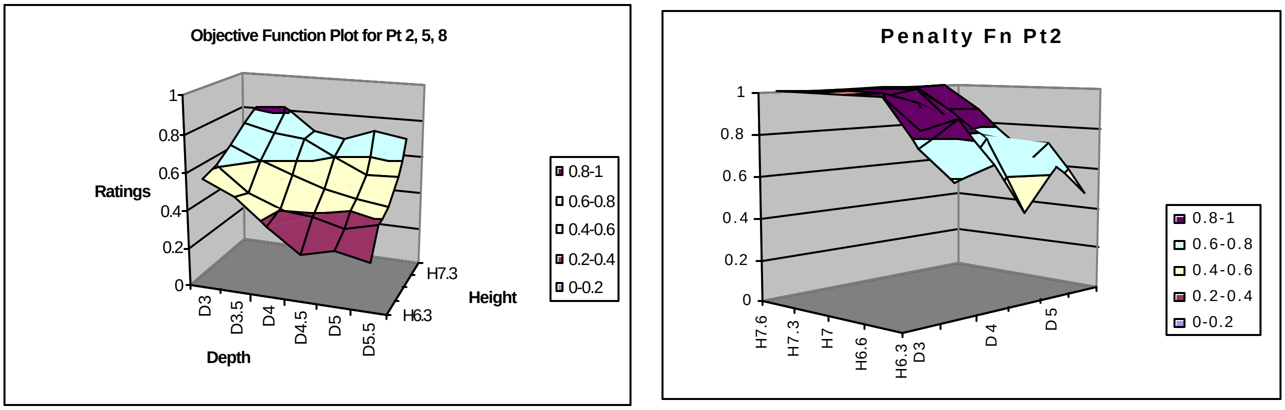


FIGURE 6.1 RATINGS FOR LIGHTSHELF DEPTH AND HEIGHT

6.2 Research on optimization in architecture

6.2.1 Nonlinear relationship.

If the relationships between objective functions and constraints appear to be nonlinear, a Lagrangian Multiplier can be used. To solve the problem, constraints and objective functions must be combined in terms of objective function without constraints. It involves minimizing or maximizing objectives subject to both equality and inequality constraints, with a goal of finding the optimal vector of design parameters or variables.

It appears that this method is good for most architectural problems, since variables to be optimized are all dependent and the objective function is not separable. An appropriate objective of an optimization algorithm is to minimize the error of the least squares, such that

$$E(p) = \left[A_{target} - A_{iteration}\right]^2$$

The earlier study by Law (1997) on daylighting design using a nonlinear optimization technique, employed the most popular and frequently used tool—the modified Newton's method called Levenberg-Marquardt algorithm (Law, 1997). Newton's method begins to search for a root with an initial guess, then finds the tangent line by finding the derivative of the function of that value. The Levenberg-Marquardt method decides what direction and slope to take after the iteration. Then the process is repeated until the difference between the root of the tangent and the guess is minimal. It calculates the next parameters of the windows to test based on the previous errors. It is guaranteed that the error will be decreased by following the steepest descent. Results show that this tool works well in optimizing window parameters when proper initial parameters have been assigned. Therefore, it is a good local search method.

However, some architectural problems exhibit several minima; therefore, it is not applicable for these problems, which require global search method. The optimized parameters can be achieved within a few iterations. Another disadvantage of nonlinear problems is the highly increased computation time as number of variablse increases. Levenberg-Marquardt method requires storage of the full Jacobian matrix, which represents a limitation for architectural problem when the number of unknowns increases. It solves nonlinear least squares problems efficiently when the residuals are small.

6.2.2 Dynamic Programming.

This is an approach to sequential decision making in optimizing problems. It is a useful optimization technique where nonlinearities are found. Gero (1977) has demonstrated that a problem can be handled by dynamic programming to produce the guaranteed global optimum which is not ensured by the originally proposed nonlinear programming method.
Characteristics: Dynamic programming is not a set of methodology, but is an approach to optimization. Thus, it requires that the problem be organized as a serial multistage system of a set of stages, which are joined together in such a way that the output from one stage becomes the input to the next (Nemhauser, 1966). This is a considerable intellectual challenge; dynamic programming is high in logic and low in mathematics.

Conditions: There are two conditions that a problem must satisfy in order to be solved using dynamic programming.

- The objective function must be separable, so that it can be divided into a series of contributing stage returns.
- It must be possible to organize the problem in the required serial structure in such a way that a later decision does not invalidate earlier decisions.

Advantages: It has properties which make it particularly appropriate for the kind of problems with which design is concerned, since it will handle discrete, discontinuous, and nonlinear relationships. Moreover, in most dynamic programming, the greater the number of constraints on variables, the more efficient the optimization procedure.

Disadvantages: It lacks a standard methodology and requires more thought about the structure of such problems. Since it does not have a standard form, the amount of computation can become excessive with multidimensional problems. Fundamental difficulties lie in problem formulations and the high cost of treating multidimensional problems.

6.3 A new approach using an optimization algorithm in lighting design

The new design approach implements the inverse method that seeks to apply scientific information involved in the decision-making process. In this research, a designer enters a desired daylighting performance condition, including all constraints. Given a room description, a searching technique, or Genetic Algorithm (GA), is used to determine a range of best design solutions. The evaluation for the decision-making tool will generate multiple alternative design schemes, as well as comparisons with the building design performance. However, during this evolutionary process, the design decisions still require direct human involvement, since an architect is the prime interpreter standing between physical form and human needs.

Figure 6.3 illustrates the general algorithm of the system. The main script or the controller is written in C++ to read input data from Graphic User Interface and to link search engine (GA), lighting simulation tool (Radiance) and the objective function. The scripts are designed to be flexible, so that the designer can easily change the design parameters and visualize the results from Radiance and the system. Once all data have been entered, the controller transforms the variables into GA parameters and also generates an objective function. It first selects a set of initial design variable values. These initial values are then sent to a modeler to convert to room, window, and its environment description into Radiance format.

Another script is written for Radiance to update calculation variables from GA and the designer. The inputs are transformed into Radiance formats and executed to provide requested outputs, which are values of lighting level and glare and renderings of the space. Then the outputs are evaluated with regard to the objective function created by the main script. Utilizing results of lighting analysis, the objective function calculates the design performance and returns the value to the optimization algorithm. GA takes scores from the objective function, and variables and constraints from the user, in order to find the next best set of configurations. The optimization algorithm modifies the design variable values in an attempt to improve its performance while satisfying all constraints. The loop continues until it meets stopping criteria (Figure 6.2 and 6.3). Each generation, the system provides quantitative and qualitative outputs on the computer screen so that the designer could understand and learn the information during the evolving process. The renderings could show the space as a dynamic space which changes temporally through course of day or over the interval of a few minutes or three months. This would serve to enrich the lighting design process. The process applied within this work possesses the characteristics that bring about the qualities of craft in a non-physical medium.

For a simple problem of lightshelf, an automated program has been written so that the designer could use it to search for design solutions. Flowcharts in Figure 6.4 illustrate a new program in detail. It shows how inputs are manipulated and sent to Radiance (.rad files), GA, and objective function. Then all information is calculated by the main function. Outputs are written in Radiance format in order to present the renderings on a computer screen. For more variables, the program is not considered to be a user-friendly program. More development could be developed for a better user interface.

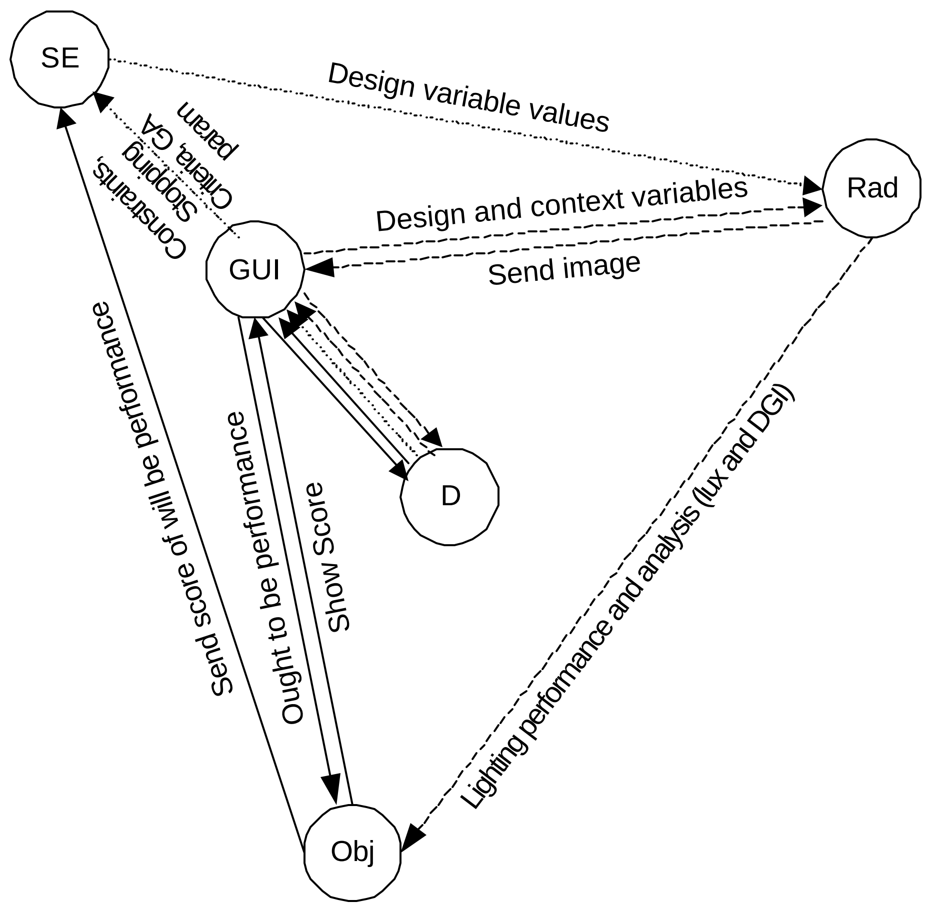


FIGURE 6.2 INTERACTION AMONG MOD ULES IN DESIGN AND OPTIMIZATION PROCESSES

SE	Search engine (Genetic Algorithm)
RAD	Radiance software
GUI	Graphics user interface
D	Designer
OBJ	Objective function

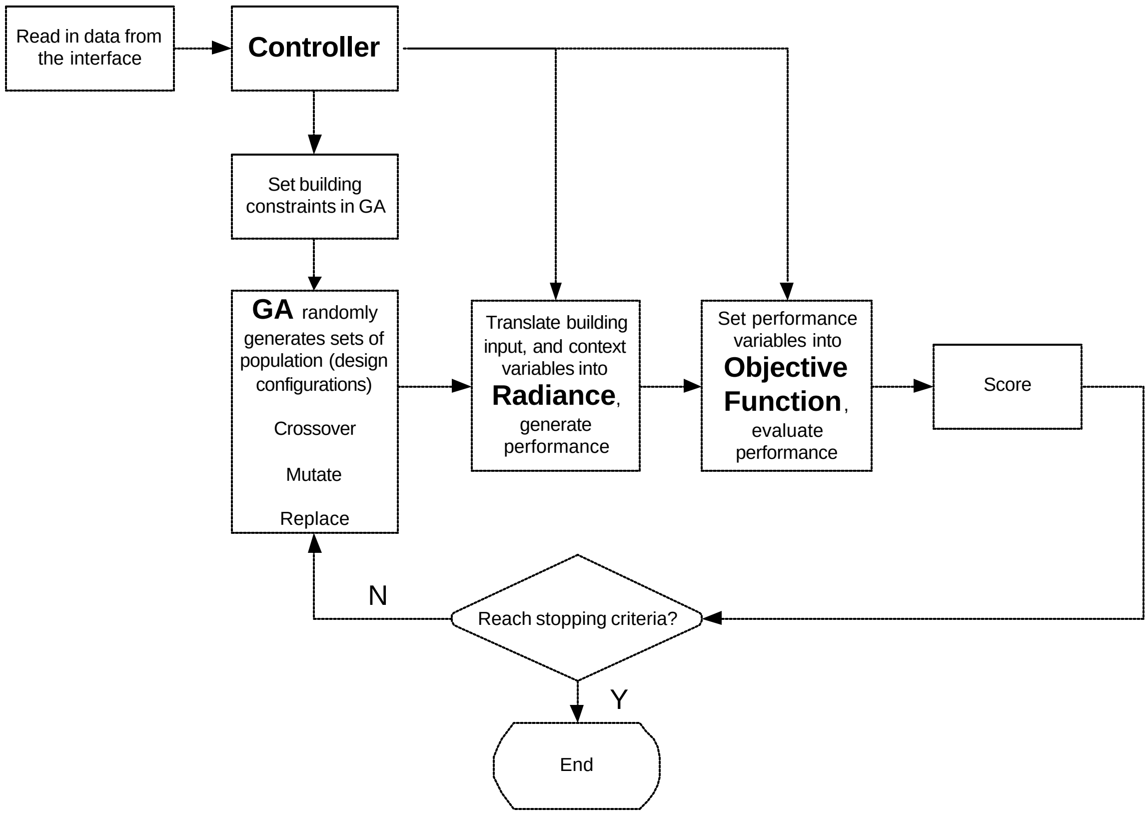


FIGURE 6.3 SYSTEM ARCHITECTURE AND PROCESS

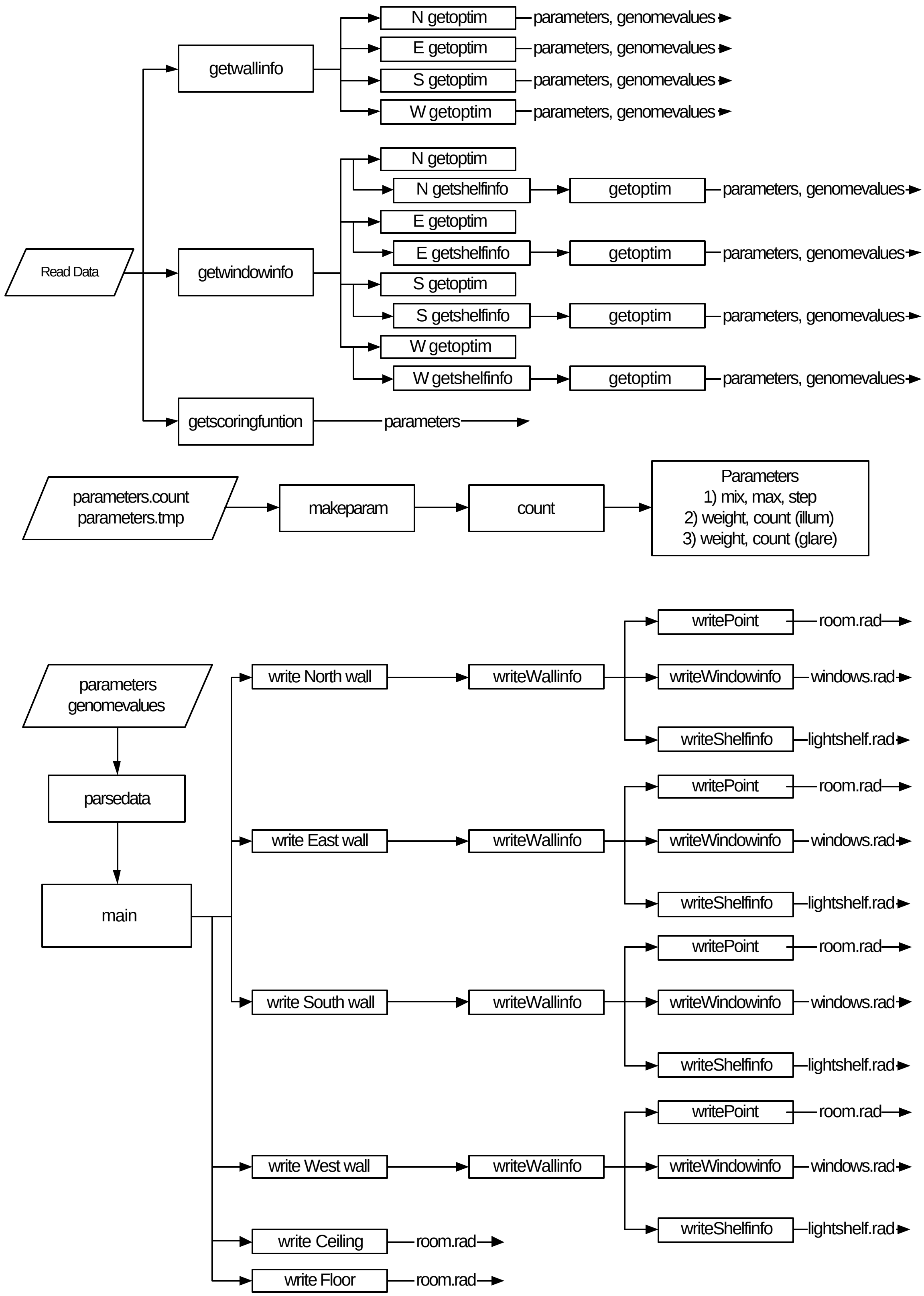


FIGURE 6.4 DETAILS OF A SIMPLE PROGRAM TO OPTIMIZE LIGHTSHELF PARAMETERS

Figure 6.5 presents a new diagram that incorporates history database table. It has been added into the optimization routine in order to speed up the design process. If GA assigns values of variables that have already existed by comparing to the information in the database, the system will not call Radiance. Instead, it will give out the score. If GA assigns such configurations that have never been called or assigned, the controller will then add those values and update the values and associated scores into the table. This process reduces optimization time by about 50%.

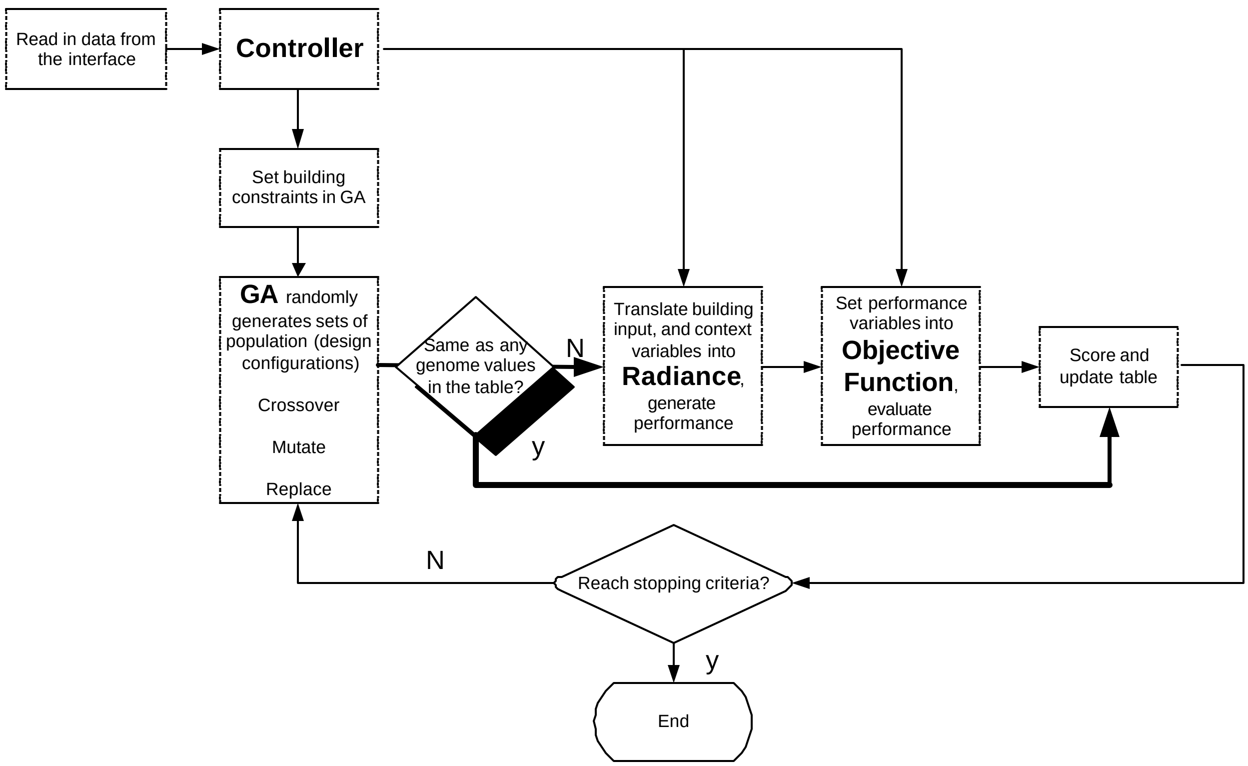


FIGURE 6.5 AN OPTIMIZATION SYSTEM WITH A HISTORY DATABASE

6.4 Genetic Representation

Many researchers have proved that genetic algorithms (GAs) typically perform well on problems in which the objective and/or search space combine both discrete and continuous variables (Horn and Goldberg, 1995; Manikas, 1996). Furthermore, they are effective for searching large and multidimensional spaces, since they operate on a population of solutions rather than an individual one alone, and they use no gradient method. For these reasons, GA is chosen to perform solution searches for the architectural problem presented in this thesis.

This research describes a genetic algorithm approach to a new design process. It describes the creation and implementation of tools to assist in developing the model in terms of architectural genetics. In addition to the architectural representation, this thesis presents a structured method for defining and evaluating multiple constraints and objectives.

6.4.1 The nature of analogy

Architecture has frequently drawn inspiration from nature—from its forms, structures, building envelope, and building systems, and from the inner logic of morphological processes. It can be said that architecture is a man-made environment, which is a major part of the global eco-system. Man and nature share the resources for the building. Architectural concepts can be described in the genetic code-script. In this research, the primary task is to develop a new design process and tool using a method of "nature's" information systems, or so-called genetic algorithms.

Invariably, conflicts occur amongst the objectives. The greater number of objectives to be considered, the greater the number of possible conflicts. Multiple objectives are presumed to be a good solution. However, a mechanism is required for defining their relationship in order to decide which objectives are more important.

6.4.2 Genome

Genetic algorithms mimic the processes of natural evolution that were originally proposed as a general model of adaptive processes (Holland, 1975). The basic genetic analogy in design utilizes a model of the Darwinian theory of "survival of the fittest." Each iteration of the algorithm is called a generation. Each set of design configurations, or individual, is represented by a string, or genome. Each string consists of characters or genes, which have specific values or alleles. During each generation, the individuals of the current population are rated for their effectiveness as solutions. Based on the ratings, a new population of candidate solutions is formed using specific genetic operators. Selection and recombination operators then find high-performance design configurations. A general genetic algorithm is presented below (Back, Hammel and Schwefel, 1997).

```
T := 0;
initialize P(t);
evaluate P(t);
while not terminate do
        P'(t) := variation [P'(t)];
        Evaluate [P'(t)];
        P(t+1) := select [P'(t) U Q];
        T := t+1;
od
```

where

P(t) = a population of individuals at generation t.

Q = a special set of individuals that might be considered for selection.

P'(t) = an offspring population which is generated by genetic operators.

This genetic design technique models inner logic rather than external form. The following is a description of how to map the genetic analogy in design. To understand more about GA processes, see an illustration Figure 6.6.

- Fitness represents performance of building design, which is the sum of scores of both light level and glare level.
- The chromosome or genome represents a set of variables to be investigated, such as lightshelf depth and height.
- The allele set represents bounds or parameters and constraints. For example, the allele set of lightshelf depth ranges from 3' to 5.5', at discrete steps of 0.5'.
- The evolutionary processes, controlled by genetic operators, map the processes of design. In a genetic process, successful genes form a gene pool, which is adapted to the environment of the interaction. In this case, the environment represents user response, or the interaction of a lighting designer.

A Genetic Algorithm program written by Wall in the C language has been chosen for this thesis because of its accuracy and flexibility. The following sections explain the steps and rules of the genetic algorithms (see http://lancet.mit.edu/galib-2.4 for more detail). A real number genome is selected, since nine times out of ten, a real number genome will perform better than a binary string genome; because the actual performance on this problem are real values, then chances are the real number genome will do better (Wall, 2000).

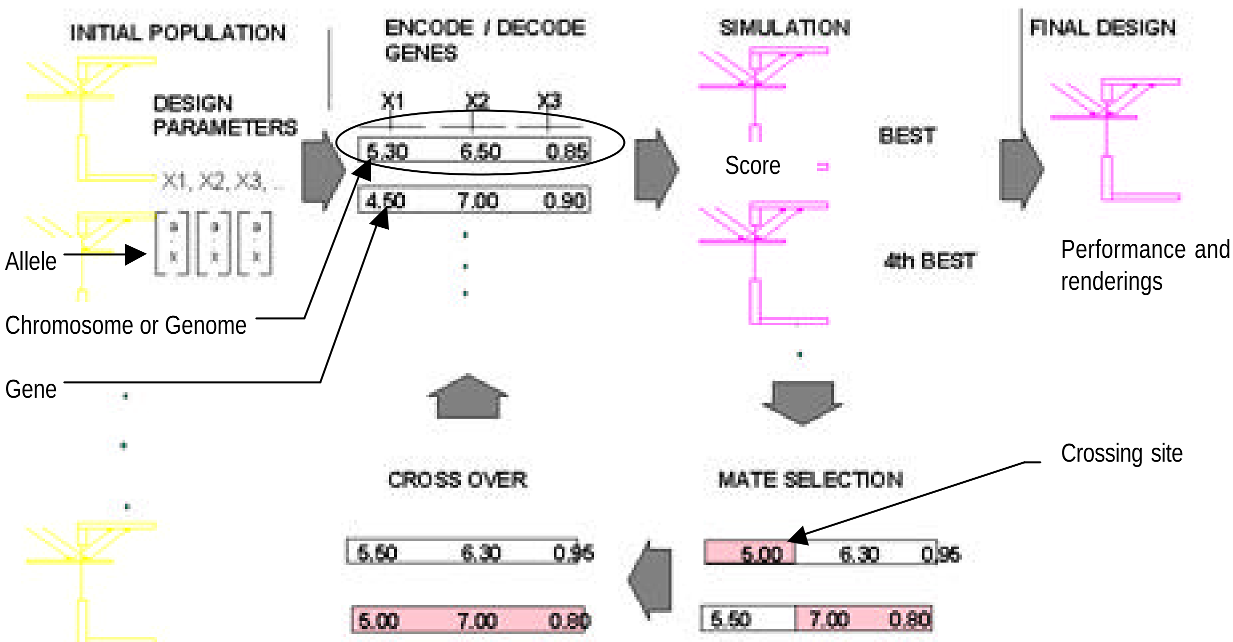


FIGURE 6.6 GENETIC ALGORITHM PROCESSES

6.4.3 Genetic Operators

- Create Initial Population

Populations of P genomes, or sets of window variables, are randomly generated to create an initial population specified by a designer. Each individual must represent a valid solution without violating constraints.

- A New Initializer

A new initializer has been created in order to generate better genomes that will help the system to converge faster. Example of the use of this new initializer is presented in Chapter 10. It is customized such that the designer could take preferred initial configurations. The result in Chapter 10 is that the system has converged within generation 3, which is about 60% faster.

- Select Parents

Each individual has a fitness value, which is a measure of the quality of the solution represented by the individual, or genome. The fitness value depends on criteria established by a designer. The better an individual performs, the greater is the chance for the individual to live a longer time and generate offspring. The selector used here is the roulette wheel method.

- Crossover

After two parents are selected, crossover is performed on the parents to create two offspring, or genomes. Crossover is applied to selected pairs of parents with probability equal to a given crossover rate. At this stage, parents pass segments of their own genes on to their children. The effect of this operator is that some children are able to outperform their parents if they receive good genes from both parents. Generally, the recommended crossover rate should be high, about 0.75 – 0.95 (Obitko 1998; Schaffer, Caruana, Eshelman, and Das 1989). After numerous simulations have been done, arithmetic crossover, with a value of 0.9, is chosen for the daylighting design problem, since it yielded the best result (Figure 6.7).

One-Point Crossover: Each parent strings are divided into two segments at a randomly picked site. Then, child C_1 is generated by concatenating the first segment of the parent P_1 and second of P_2 and vice versa for C_2.

Two-Point Crossover: It operates like the previous method in principle. The difference is that two random crossing sites are used.

Uniform Crossover: At each position *i*, it is decided randomly if C_1 is assigned the corresponding value of P_1 or P_2. Similar method is applied for C_2.

Arithmetic Crossover: At each position *i*, it is decided randomly if C_1 is assigned the corresponding value of average P_1 and P_2. Similar method is applied for C_2.

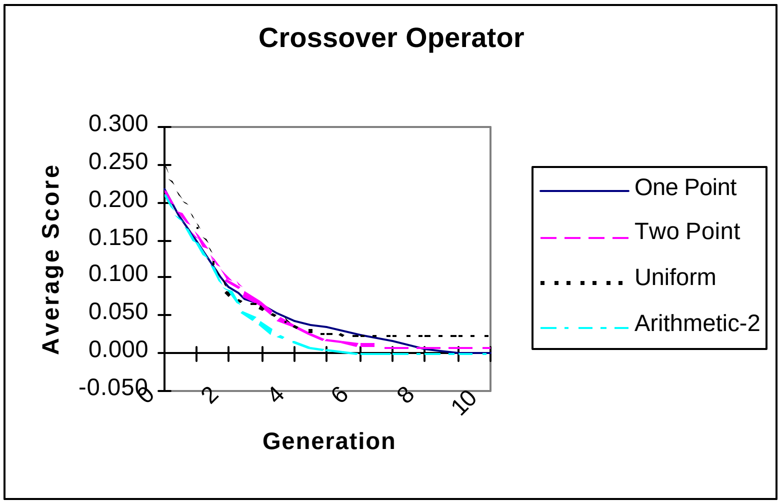


FIGURE 6.7 PERFORMANCE OF DIFFERENT TYPES OF CROSSOVER OPERATORS

- Mutation

The crossover may produce an offspring that does not solve a particular problem, since crossover only exploits current gene potentials. For this reason, a mutation is needed to alter an offspring. It randomly adjusts bits in the offspring so that its bit pattern is valid. The most common way of mutating is to flip a bit with a probability equal to a given mutation rate (Jang, 1997). Recommended values are 0.001 and between 0.005 to 0.01 (Back, Hammel, and Schwefel, 1997). The mutation method used for this research is Gaussian mutation, with the very small probability of 0.01 such that good genes obtained from crossover will not be lost.

- Update Population

The creation of two offspring increases the size of the population to P + 2. To maintain a constant population size of P, two individuals will be eliminated from the population. The percentage of population that will be replaced each generation was set to 5. An algorithm called Deterministic

Crowding GA is selected for this architectural problem. It compares offspring against one of its parents. It then replaces the two lowest-fitness genomes with the best values, with regard to the most different between the parents and the children. Another type of genetic algorithm, Steady State GA is similar to the Deterministic Crowding GA, except for the replacement criteria. With each generation, the Steady State GA creates a temporary population of individuals, adds these to the previous population, and then removes the worst individuals in order to maintain its original size. The new offspring may or may not be used in the population, depending on whether they are better than the worst in the population.

- Terminate

The termination function determines when the GA should stop evolving. Two popular forms of stopping criteria are if the system finds a solution, then stop; and if the system reaches a certain generation, then the algorithm stops. This research uses later method since the purpose is to seek other possible solutions in design. The results are useful in the learning process since they can be compared and that indicates trends for better solutions.

The next section explains lightshelf parameters. Design variables, preferences, and constraints are established. Then introduction on how to model architectural representation into GA has been described. A simple room space was modeled and run using GA to compare results from recommended lightshelf values from existing research. More GA parameters were then explored.

Chapter VII: Daylighting Systems and Parameters

The interest in daylighting in recent years has resulted in proposals for a number of architectural techniques designed to increase daylight availability in building interiors. There are generally two main methods employed to bring daylight into interior spaces: toplighting and sidelighting strategies (IESNA, 1993). Most of the time, an object set by an architect was to make the windows and skylights large enough for the darkest overcast days. With those designs, all beautiful sunny days are likely to be a problem to be corrected by shades and blinds that are likely to be in place when they are not needed. If there is no one is clear responsible for paying the bill or controlling the shades or lights, automated systems are a necessity.

However, it is not necessary for the need of new controls or value engineering as long as application of well established principles and design philosophy has been applied. It is challenging to optimize lighting design from different angles of sunlight that are harder to control in side lighting than as top lighting. This chapter describes one of the two methods, which is the lightshelf system. Later sections give initial design models based on an optimization technique.

7.1 Lightshelf System

Lightshelves are horizontal solid fixtures that are positioned at right angles to exterior, interior, or both interior and exterior sides of a window. The three types of shelves can have either single or double openings. The single opening refers to a clerestory window above the shelf and an opaque wall below it. The double opening divides the aperture wall into two parts: a view window below the shelf and a clerestory window above it. An exterior lightshelf will shade the outside of the window, reducing solar heat gain. An interior shelf provides better visual protection from sun glare. The upper surface of the shelf should be coated with a white or reflective covering, which allows both direct and diffuse light falling on the surface to be reflected into the room. In a study conducted by Aizlewood in 1993, lightshelves were found to be the simplest and the most efficient daylighting systems compared to prismatic glazing, mirrored louvers, and prismatic film systems.

Research into lightshelves began in the early 1950s at the Building Research Station (BRS). The research problem was to adequately light a deep hospital ward using daylight alone, while still retaining visual comfort for patients in beds near the window. Measurement in a scale model conducted in 1951 revealed that daylighting factors throughout the ward improved with the lightshelf (Hopkinson, 1951). The available daylight was spread more uniformly, improving visual conditions within the ward, especially near the window.

Measurement of Lightshelf Performance

Two identical full-scale model offices were used to test the performance of innovative daylighting systems (Aizlewood, 1993). The offices were south facing and each was 9.00 m deep, 3.00 m wide, and 2.70 m high. The internal shelf used was 1.00 m deep, and 2.08 m high. Measurements were taken in summer, winter, and at equinox (spring/autumn). Each room contained six illuminance sensors at the working plane height, while on the roof above the rooms, an array of sensors recorded illuminance, irradiance, and sky luminance data.

Under overcast skies, the lightshelf reduces illuminance by 5–30%, with the least reduction occurring in the back of the room. On a sunny day in spring and summer, the illuminance in the back of the room is reduced by 0–20%. An external shelf was not used because of the difficulty of fitting one to the building. A glare measurement was not taken either, although CIBSE (The Chartered Institution of Building Services Engineers) recommends a limiting glare index of 19 for general offices. Because of the limitations of the experimental facility, and time available, it was not possible to examine the effects of changing room and lightshelf geometry, or of external obstructions. Therefore, there is a need for a computer program to predict room and lightshelf geometry, given basic room geometry, site, location, and visual performance.

Listed below are suggestions from Littlefair and Lam on some configurations that are used for initial room geometry for the optimization process in this research.

1. Lightshelves work best with a high ceiling—ideally, 3 m high or more.
2. An internal lightshelf should not be too deep. A depth roughly equal to the height of the clerestory window head above the shelf is reasonable.

3. A deep external shelf provides better shading but reduces perimeter illuminance. A depth equal to the shelf height above the working plane is a reasonable compromise.
4. Both internal and external shelves should be as reflective as possible.
5. Use high-reflectance ceiling cavities.
6. Maximize other reflectance, such as ground, lightshelf, and room surfaces.

7.2 Parameters

There are many factors that make the sidelighting concept an efficient daylighting system. First, window size should be as high as possible for horizontal tasks and as low as possible for vertical tasks (Abdulmohsen, 1995). Second, glazing type offers the designer a feature with which to control and manage quantity of daylight within a building. Third, a shading device for glare, daylighting distribution, and heat control is one of the most difficult problems to overcome in daylighting (Robbins, 1986). It is important to note that there are several properties that are affected by the sun, such as orientation, reflectance, slope, and size. Fourth, interior surfaces are very important in daylighting design, since they determine the internally reflected components that reduce glare sensation caused by the windows. Design variables for lightshelves employed in this research are presented below.

1. Height
2. Depth (internal, external, or combination)
3. Shading or transmittance of lightshelf
4. Finishes or reflectance of lightshelf
5. Slope of the shelf
6. Location and size of window
7. Type of glazing
8. Room surface reflectance (ceiling, wall, and floor).

A summary of variables involved in this study is shown in Table 7.1. These variables concern the lightshelf system and continuity of open office space. These values were used in the next two chapters. The results were then compared to those found by Littlefair and Lam.

TABLE 7.1 VARIABLES, PARAMETERS, AND CONSTRAINTS FOR PARAMETRIC DAYLIGHTING STUDY

Concept	Variable	Parameter	Constraint
Exterior condition	Solar position Sky condition Season Time	Helsinki, Toronto, Fort Worth, Texas Clear, overcast Summer, winter, and equinox (vary) 9, 12, 3	
Interior condition	Orientation Ceiling reflectance Wall reflectance Floor reflectance Room geometry	S, E, N, W 0.0–1.00 0.0–1.00 0.0–1.00 constant	 Value must be < 1 Value must be < 1 Value must be < 1
Lightshelf	External shelf height External shelf depth External shelf slope External shelf transmittance External shelf upper reflectance External shelf lower reflectance	6'–ceiling height 0'–8' -90°–90° from horizontal 0.0–1.00 0.0–1.00 0.0–1.00	Value must be > 6' Value must be < 8' Value must be between -90° to 90° Value must be < 1 Value must be < 1 Value must be < 1
Window	Width Height Location Glazing transmittance	1'–wall width 2'–ceiling height 0'–(wall width –1) 0.0–1.0	 Value must be < 1
Performance	Horizontal Illuminance Vertical illuminance Daylight glare index	See Figure 7.1	See Figure 7.1

7.3 Objective function

Figure 7.1 illustrates an example of objective functions. In solving practical problems, a designer often wants to optimize more than one performance at the same time. The measures may conflict with one another, and it may be unsatisfactory to combine them into a single optimization objective, or reduce them in some way so that only one is optimized. The objective function, or the fitness function, is a measure of the success of each set of design configurations with respect to the desired features or performance. The goal of optimization is to minimize an objective function of such parameters while satisfying a set of constraints.

Since one lighting measure may have a more detrimental effect on the experience of one than another, each measure must be weighted appropriately (w). For each measure, different values must be penalized in proportion to their effects on an end user's experience. Figure 7.1 illustrates how different preferred values are penalized. It shows that preferred light level falls into a range of 40 to 60 footcandles (430 to 646 lux), which provides score of 0. For too dark and too bright illuminance levels of 30 footcandles or 323 lux and 120 footcandles or 1292 lux are not desired, therefore their scores are set to 1. The same principle is applied to the second objective function; glare level.

According to Table4.1, recommended DGI (just intolerable) should not exceed 28. The three curves presented below are adapted from the IESNA recommended DGI values. Since most designers prefer to work with qualitative description instead of quantitative numbers, the three curves represented three levels of how the designers would treat the importance of glare issue; critical, important, not important. These values can be set as default values for them to choose from. Dotted line represents that glare is treated as critical. DGI values of 18 or less are preferred and any numbers in between 18 to 28 are penalized. It is unacceptable that the DGI value at a given point exceeds 28. Dash line and bold line indicate that glare criteria are important and not important respectively.

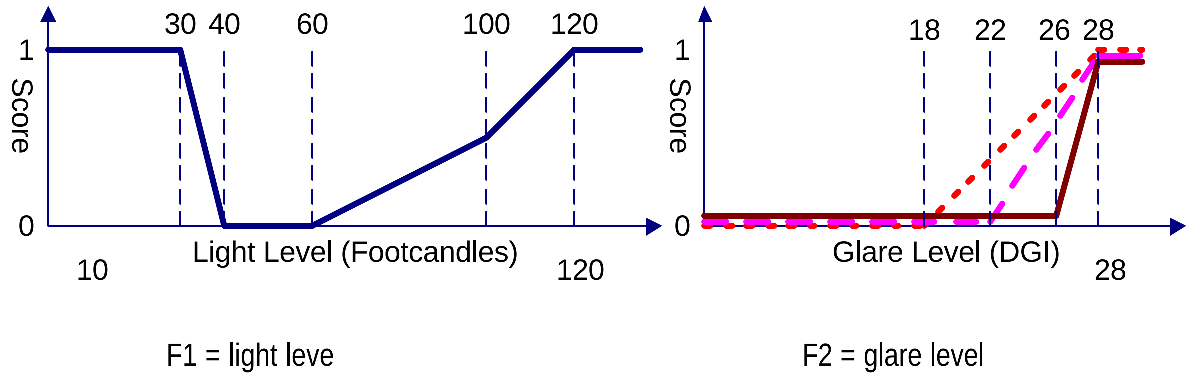


FIGURE 7.1 EXAMPLE OF PERFORMANCE VARIABLES AND CONSTRAINTS EMPLOYED IN THIS RESEARCH.

Chapter VIII: Daylighting Design Problem

This chapter describes assumptions and the solution method in the problem model, defines the application domain of this research, and then details the technique used to perform and implement objectives.

8.1 Problem Model

This section explains the design optimization process and its necessary components. In daylighting design optimization, the designs of devices or strategies are optimized so that they exhibit maximum performance, or preferred lighting performance, subject to a given set of functional requirements and constraints.

8.1.1 Daylighting optimization process

Before conducting a design optimization, the problem description should be set forth as a qualitative statement, and then formulated as quantitative statements (e.g., maximize the amount of daylight and minimize the amount of direct sunlight within a room subject to a maximum window area). The process begins with the definition of design criteria, which influence design configurations. Design criteria typically used in daylighting optimization include, but are not limited to, cost, dynamic behavior of color and intensity of light, lighting distributions, glare, and energy gain or loss. Next, design variables—which are parameters controlling design performance—and context variables, (i.e., location, sky, climate, and building geometry, etc.), are defined. Then, an objective function, or the desired lighting conditions, will be developed by a designer. Taking as input a particular set of design variable values, a specific program converts the variable values into their corresponding design, analyzes the design to determine its lighting behavior using Radiance, and then calculates a quantity describing the design performance by the objective function. Finally, ranges of desired variables as well as performance constraints (ranges of desired and undesired performance) must be created. Design constraints establish a design's feasibility. Components that do not violate any design constraints are considered feasible, while those violating one or more constraints are ruled out as infeasible.

Hence, the set of optimum design variable values represents the optimum design, while the objective function measures the lighting design performance, and the set of constraints represents limitation imposed on the design's lighting behavior. The architectural problem can be modeled as follows:

Given

- a set of tasks,
- a set of objectives with which to determine a space's performance,
- a set of performance variables,
- a set of decision design variables to be optimized,
- a set of design constraints which must be satisfied,
- a set of context variables (i.e., location, sky, climate, and building geometry),
- a set of calculation options,

What is the best building design strategy producing the desired result such that all of the constraints are satisfied and the best objective measures are reached?

The general process includes the following.

- Initial geometry is established.
- The number of tasks, objectives, and constraints are specified. Each task may require a different objective function.
- Design variables, performance, and context variables are defined.
- Calculation options are specified.
- The program starts to optimize by generating renderings and their performance for the best design solutions for each iteration. Designers could then learn during the optimization process.

Objectives, constraints, and all input variables are specified at the beginning of the design process or during the formulation of the problem. Objectives determine the optimality of an architectural geometry and constraints define the feasibility of architectural space. An optimal building geometry must satisfy all of the constraints and must be at least as good as other feasible geometry. A feasible geometry must also satisfy all of the constraints. The objective function in this thesis is to minimize any number of fitness values, which are formulated and described in the next section.

8.1.2 Assumptions and Characteristics

The assumptions made determine the variations of the problem that the model will support. Described below are assumptions, characteristics, and examples about daylighting problems employed in this research.

Assumption	Description and Characteristics	Examples
Tasks	There may be more than one task Each task has its own set of requirements.	There are two different tasks in a space that require different lighting condition. The relative importance for each task is not equal. Each task exhibits different schedule for different time and/or season. The relative importance for the summer and the winter are treated differently.
Objectives	Any objective measure can be used as long as it can be resolved from a final design. Objectives may include more than one statement. Objectives determine the optimality of an architectural geometry.	Minimization of direct sunlight and maximization of daylight on a work plane.
Performance	Performance constraint for each task may have one or more sets. The value of the performance depends on the assigned values that the design and context variables have taken. It is a function of design and its context. Design specifications have an associated quality in terms of indices, levels, units, and/or degrees that can be used to evaluate performance. In this research, types of performance to be evaluated are visual quality and quantity, i.e., glare index and lighting level. There is also an option to focus on only one attribute, which is illuminance level.	According to Figure 7.1, a designer requires that preferred illuminance levels provided by daylight are about 40 to 60 footcandles or 430 to 646 lux. Illuminance levels should not fall below 30 footcandles (323 lux) and should not be greater than 120 footcandles (1291 lux).

	Transformation of desired performance to the interval score [0,1] is incorporated in this study in order to facilitate comparison of multiple objectives.	
Design variables	Design variables have relationships and may be defined in terms of the priority that each is assigned. There are two types of design variables: those related to material properties and those related to building geometric and shape properties. Variables in architectural problems can be both discrete and continuous. Most variables used in this research are discrete variables, since products could only be purchased with certain lengths or widths.	Material properties could include factors such as window transmittance and surface reflectance.
Design constraints	Design may be restricted to certain shapes or configurations. Constraints define the feasibility of architectural space. To simplify and demonstrate the study, this research focuses on square or rectangular geometry.	A lightshelf has a limited height of 6’ from floor with a maximum reflectance of 0.90.
Context variables	Sky conditions can be either clear or overcast. Ground is assumed to be a perfectly diffuse surface. Color of the sun is not taken into consideration.	
Index resolutions	There are three options for resolution ranging from slowest and most accurate to fastest and less accurate.	

8.2 Problem Formulation

It is important to note that a particular set of design variable values represents both a particular design and a particular point or location in a search space. Architectural daylighting problems have proven to be difficult problems, with several local minima, as elaborated in Chapter 6. As mentioned in the previous section concerning the optimization process, once all criteria and variables are defined, an objective function must be developed. This section defines the objective function used in the search for solutions in the search space.

Given a set of design variables, the objective function calculates and returns a value indicating its performance. Depending on the optimization techniques being used, the objective function could be maximized or minimized. A single space often accommodates a number of disparate uses, each of which has its own requirements. The objective function in this thesis is to minimize a weighted fitness value. Multiple objective functions are constructed as follows:

$$\text{Minimize } p_{obj} = \frac{\sum_{i=1}^{m} w_i f_i}{\sum_{i=1}^{m} w_i}$$

where

w_i = the weighting factor of the i^{th} individual objective function, and sum of the weighting factor is 1.0

f_i = the fitness value of the i^{th} individual objective function.

Conflicts usually occur amongst the objectives. The greater the number of objectives being considered, the higher the possibility of conflicts. Multiple objectives could be considered a good solution. However, a mechanism is required for defining their relationship in order to make decisions about which objectives are more important. Each weight w_i indicates the value of the i^{th} objective relative to other objectives. The same principle is applied for multiple tasks and locations as well as for different time of days or seasons.

The system's most powerful function is the ability to merge time within the model. Figure 8.1 shows the flow chart for calculating illuminance level and score of a set of room configuration for the whole year. This chart has been derived from the fundamental needs of design and learning process by working with a lighting designer and by studying a problem-solving process of using a physical model. The ability to represent changing sunlight patterns throughout the day was necessary during the daylighting design process. An example of the use of multiple measuring points in a space for the whole year is described and implemented in Chapter 9, a case study of a library.

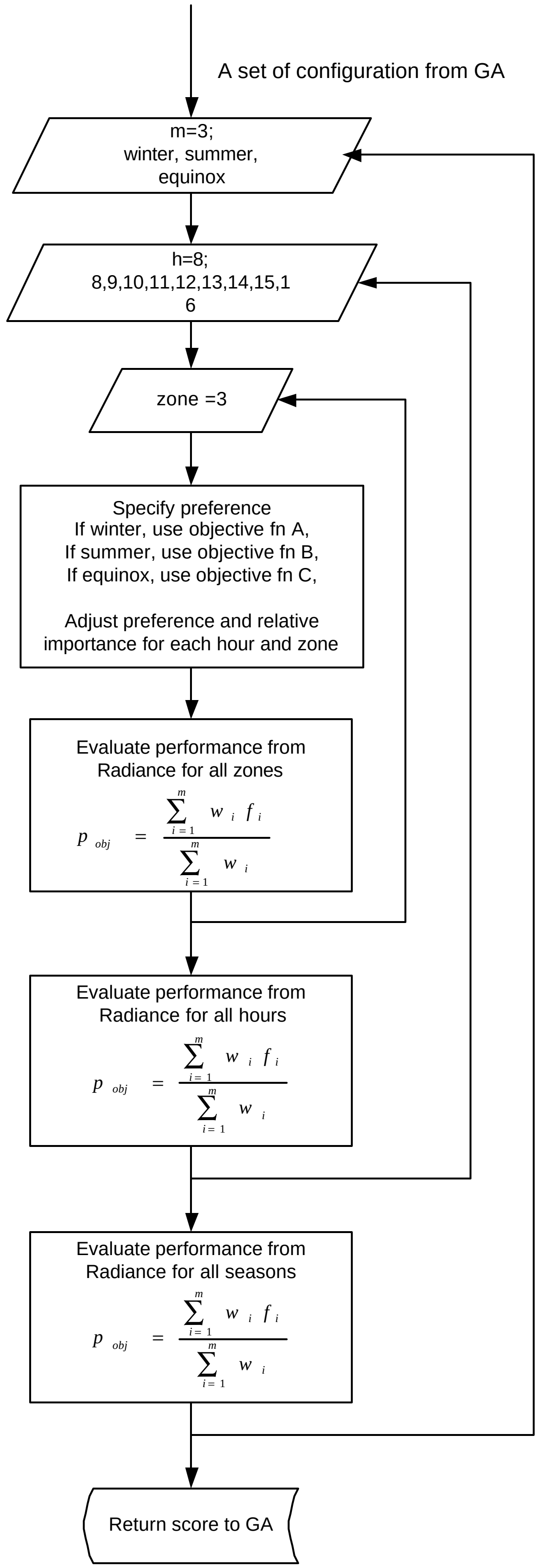


FIGURE 8.1 FLOW CHART OF EVALUATION PROGRAM FOR CALCULATING WEIGHTED SCORE

A design solution of n design variables can be written as:

$x = [x_1\ x_2\ \ldots\ x_n]$

Thus, the generalized architectural optimization problem can be expressed as follows:

Find a solution to design variables,

$x = [x_1\ x_2\ \ldots\ x_n]$

to minimize P_{obj}

subject to p constraints.

8.3 Results from Genetic parameters and processes

This thesis investigated four important issues in the new proposed process for daylighting design.

1. To test whether the proposed searching method would be able to find the best solutions.
2. To find the best algorithm that is appropriate for use in solving the daylighting design problems.
3. To investigate the effect of GA parameters: population size and operators.
4. To investigate the effect of daylighting parameters.

In the first study, the location for the testing was Boston, Massachusetts, on June 21 at 12:00 pm. To simplify the study, the only objective function (f1) is to achieve 50 footcandles or about 500 lux in the center of the room on the work plane, 2.5' above the floor. The rating function can be found in Figure 7.1. The window was south facing, with a transmittance of 0.80. The only variables are lightshelf depth and height, ranging from 3' to 5.5' at discrete steps of 0.5', and 6.3' to 7.5' at discrete steps of 0.3', for depth and height respectively. The test creates a solution space of 30 points. The room and window dimensions and measurement points are illustrated in Figure 8.3. Steady State GA, with the population size of 10, was tested against the exhaustive test, the results of which are shown in Figure 8.4. The lowest score found from the exhaustive test was 0. GA assigned the values of lightshelf depth of 5’ and 5.5’ with 6.3’ high.

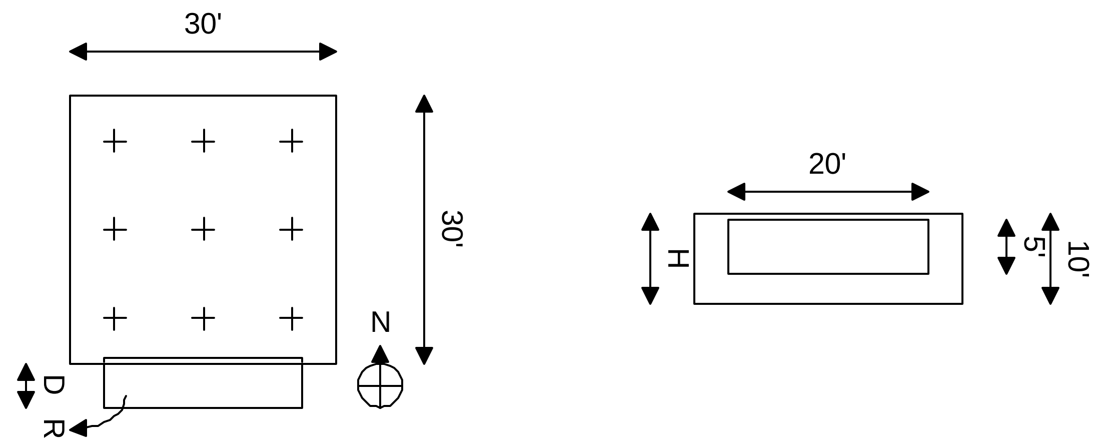


FIGURE 8.3 ROOM AND WINDOW DIMENSIONS (NOT TO SCALE)

The results from this study indicated that the local minima were found at points (5, 6.3) and (5.5, 6.3), corresponding to a lightshelf 5’ and 5.5’ deep, and 6.3’ high. GA found these two points by generation 2, which was 33% faster than the exhaustive test. The results proved that GA could be used in this proposed research.

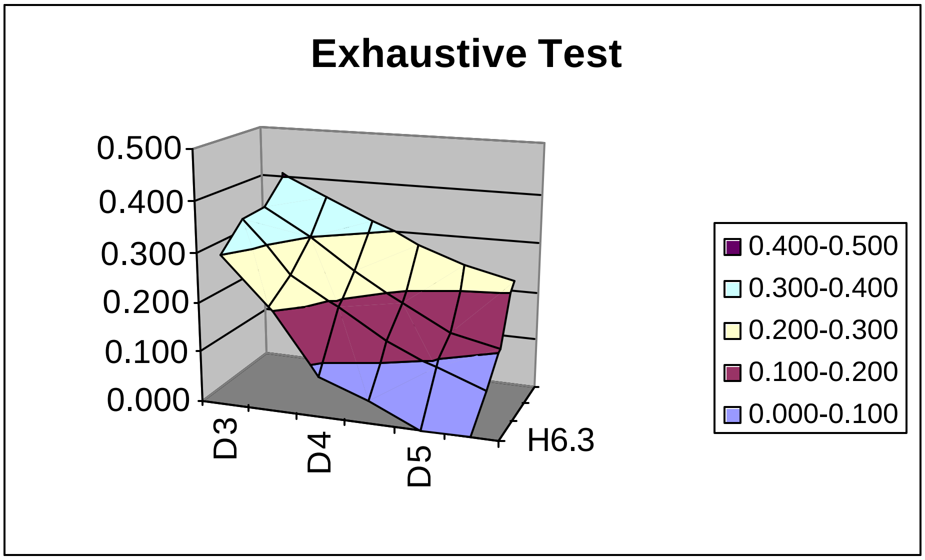


FIGURE 8.4 VALUES CORRESPONDING TO LIGHTING LEVELS

In the second study, Steady State GA was tested against Deterministic Crowding GA, using the same set of room configurations. The population size was 30. Window variables were increased from 2 to 3—lightshelf depth, height, and reflectance. Lightshelf reflectance ranges from 0.5 to 1 at discrete steps of 0.05, creating a total solution space of 330 points. Figure 8.5 illustrates that the Deterministic Crowding GA performs better than Steady State GA. Besides, the former GA provides more design solutions than Steady State GA.

In the third study, numbers of population size were varied—3, 5, 10, 20 and 30. The genetic operators tested were uniform crossover, one-point crossover, two-point crossover, and arithmetic crossover. The results from this study indicate that a larger population size provides better chance of finding solutions. There were numerous experiments for the third study. The experiment compared a GA with different types of crossover. A point was plotted for every generation. The vertical axis is the fitness of the best individual and its average seen, measured by the fitness function defined above. Since the objective function is to minimize the score, a lower curve represents better performance. Each curve is an average of 10 independent runs. The results are presented below in Figure 8.6.

It can be concluded that uniform crossover and arithmetic crossover outperforms both one- and two-point crossover for larger population size. This result is expected, since they more strongly encourages recombination. It indicates that uniform crossover and arithmetic crossover are useful when recombination is important or when the search space is very large. Although fast performance improvements occur with a smaller population size, a larger population provides better solutions. This is due to the slower accumulation of more accurate statistics when using the larger population (Spears and Anand, 1991).

Considering the results of the study of crossover operation, it is apparent that crossover can exhibit high levels of preservation, survival, and construction because it shares information between fit individuals. In contrast, mutation is implemented with a parameter that is constant during genetic algorithm search, thus preserving common alleles. A simple test has been done to investigate the effect of mutation rate on the performance of the system. Optimizations are performed using mutation rates of 0.001 and 0.01. The first generation with acceptable solutions is used as a measurement for the optimization. The result exhibits a decreasing in number of generation needed to find acceptable designs as the mutation rate increases. Therefore, based on suggestions stated in the previous chapter and this study, the mutation rate of 0.01 is chosen.

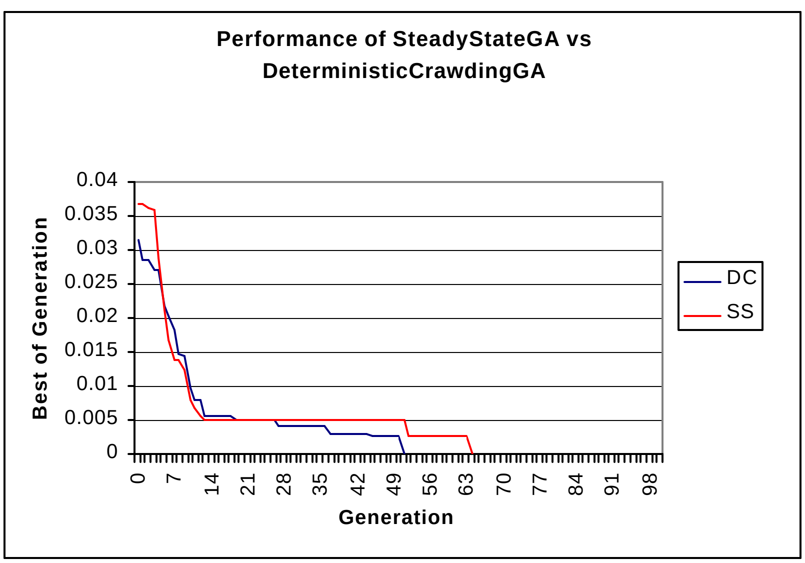


FIGURE 8.5 THE PERFORMANCE OF STEADY STATE GA AND DETERMINISTIC CROWDING GA.

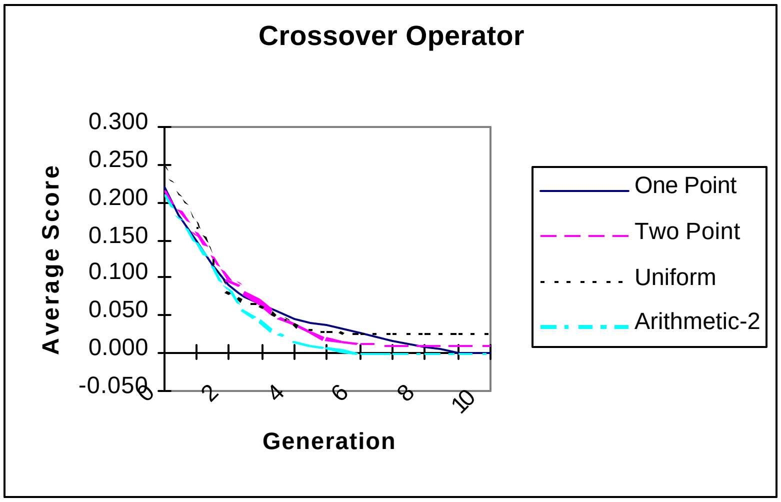


FIGURE 8.6 THE PERFORMANCE OF DIFFERRENT TYPE OF CROSSOVER OPERATORS

The summary of recommended values for GA parameters and algorithm for architectural problems is presented in Table 8.1. The criteria in selecting these values are speed and diversity of the solutions. These values are based on two to seven variables. For larger number of variables, there is a need for more study. Figure 8.5 and 8.6 seem to show that the different approaches yield similar results. However, there is a dramatic difference among different GA parameters in term of calculation time due to Radiance calculation. For instance, the system, without historical database and customized initialization, could take 5 hours to evolve in the 10th generation. Compared to a better system with appropriate GA parameters, it could converge within the 6th generation or about 2 hours or about 60% faster.

TABLE 8.1 SUMMARY OF RECOMMENDED GA PARAMETERS FOR THIS SYSTEM

Selection algorithm	Deterministic Crowding
Population size	20 - 50
Mutation rate	0.01
Crossover rate	0.9
Number of generation	10-20
Stopping criteria	Number of generation

Finally, more daylighting design parameters were investigated. GA parameters were based on information derived from the first three studies—population size of 100, arithmetic crossover of 0.9, and Gaussian mutation of 0.01. The effects of the objective functions were investigated as well. The objective functions were to achieve only the desired lighting level and then to achieve both desired lighting level and glare index. The variables were extended from 3 to 7, providing a solution space of more than a half-million points. Those variables are lightshelf depth, height, and reflectance, window transmittance, and wall, floor, and ceiling reflectance.

Figure 8.7 compares the average scores from 10 individual runs derived from different objective functions. The first one takes both f1 (light level) and f2 (glare), with weighting factor of 0.5, into account. The objective function for the second simulation considers only light level without glare. It shows that solutions to the objective function with glare are harder to achieve than the one without glare. It is standard for conflicts to occur among the objectives. The greater number of objectives that are considered, the more the possibility for conflicts increases, which, in turn, increases the difficulty in solving the problem.

Generation #	With Glare	Without Glare
0	0.032	0
15	0.006	0
30	0.004	0
45	0.003	0
60	0	0
75	0	0
90	0	0
Convergence at generation number	24.8	0
Best genome found	~5	many

Figure 8.7 Effect of the objective functions

Figure 8.8 illustrates the best individual or the best set of configurations. The longer and the deeper the lightshelf, the better the illuminance distribution in the room. This finding supports Littlefair and Lam's studies. However, for a higher reflectance of the lightshelf, it is not necessarily true that lowering the lightshelf will achieve the desired illuminance, as shown in Figure 8.8. In this case, for the highly reflective lightshelf, the lower levels of the lightshelf could provide too much illuminance on the work plane. Additional variables, that include lightshelf depth and height, floor reflectance, and window transmittance, imply significant effect because GA assigned the same values for them over and over until the system has converged. When these values were different, they affect total lighting performance by increasing their fitness values.

The differences between the solutions shown above, suggest that the use of an optimization tool may not only provide increased design quality in terms of visual perception, but also present variability and creativity in the design. Although solutions optimized for visual performance do not always represent optimal behavior, those solutions provide information gained during the design optimization process. Besides, the designer may modify the results provided by the program in making design decisions, using information gained from the genetic algorithm.

Best Genomes	Depth	Height	Shelf Ref	Wall Ref	Flr Ref	Ceiling Ref	Win Trans	Lux	DGI	Quan	Qual	TotScore
2 variables	5.5	6.3	~	~	~	~	~	~	~	0		0
	5	6.3	~	~	~	~	~	~	~	0		0
3 variables	5.5	7.2	1	~	~	~	~	~	~	0	0	0
7 variables	5.5	7.2	1	0.85	0.1	0.85	0.75	575	21.92	0	0	0
	5.5	7.2	1	0.85	0.1	0.8	0.75	543	21.9	0	0	0
	5.5	7.2	1	0.85	0.1	0.75	0.75	512	21.96	0	0	0
	5.5	7.2	1	0.85	0.1	0.7	0.75	481	21.96	0	0	0
	5.5	7.2	1	0.8	0.1	0.85	0.75	570	21.96	0	0	0
	5.5	7.2	1	0.8	0.1	0.8	0.75	539	21.98	0	0	0
	5.5	7.2	1	0.8	0.1	0.75	0.75	508	22	0	0	0
	5.5	7.2	0.95	0.85	0.1	0.85	0.75	556	21.94	0	0	0
	5.5	7.2	0.95	0.8	0.1	0.85	0.75	551	21.97	0	0	0
	5.5	7.2	0.95	0.8	0.1	0.8	0.75	521	22	0	0	0
	5.5	7.2	0.9	0.85	0.1	0.85	0.75	538	21.96	0	0	0
	5.5	7.2	0.9	0.85	0.1	0.8	0.75	508	21.97	0	0	0
	5.5	7.2	0.9	0.85	0.1	0.75	0.75	479	21.98	0	0	0
	5.5	7.2	0.9	0.8	0.1	0.85	0.75	533	22	0	0	0
	5.5	7.2	0.8	0.85	0.1	0.85	0.75	501	22	0	0	0

FIGURE 8.8 BEST GENOMES FOR DIFFERENT VARIABLES

Chapter IX: Case studies

This section demonstrates the application of a genetic algorithm based on real architectural spaces in which daylighting plays an important role. The studies show that the algorithm finds the solution faster than the traditional design process and the tool can be considered a learning tool. From experience using it as the designer, I have learned and discovered many interesting facts during the evolving process as described in this chapter. Moreover, the evolved genes and/or initial guess from designer's experience represent design features that can be reused later in the solution of similar problems. The effect of this is that the tool becomes more efficient with use. The examples used are the IBM Toronto Laboratory, Canada, the Wexner Center for Visual Arts, Columbus, Ohio, and a public library, Albany, New York.

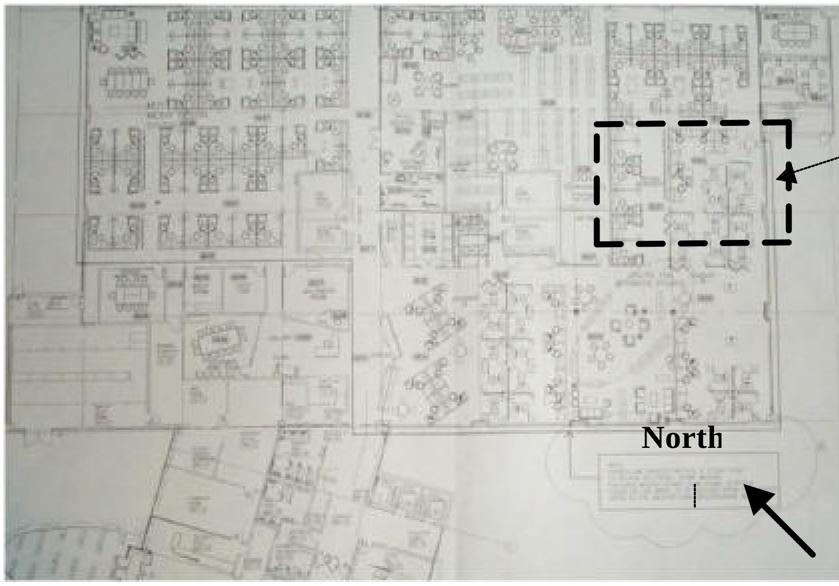
9.1 IBM Toronto Laboratory, Toronto, Canada

The first case is IBM in Toronto, Canada. The southeast facade was floor to ceiling double-glazing curtain wall, which produced an excessive amount of daylight, causing glare from unwanted direct sunlight. By simulating the existing space in Radiance, Figures 9.2 and 9.3 confirm the glare problem revealed by users' preferences found from the experiment. Please see Appendix B, C and D for more detail on the experiment conducted at the IBM. The walls and ceiling are painted with highly reflective materials. The window area is large allowing daylight to penetrate into the interior space that causes excessive glare and unwanted direct sunlight. This section presents design constraints for a software-design office, derived from observations and interviews with staff.

- The staff needs to sit where they can see daylight or its effect, which connects them to the outside world.
- The space must be flexible and adaptable for different weather, time, mood and functionality.
- There should not be direct sunlight falling on computer screens and working surfaces.

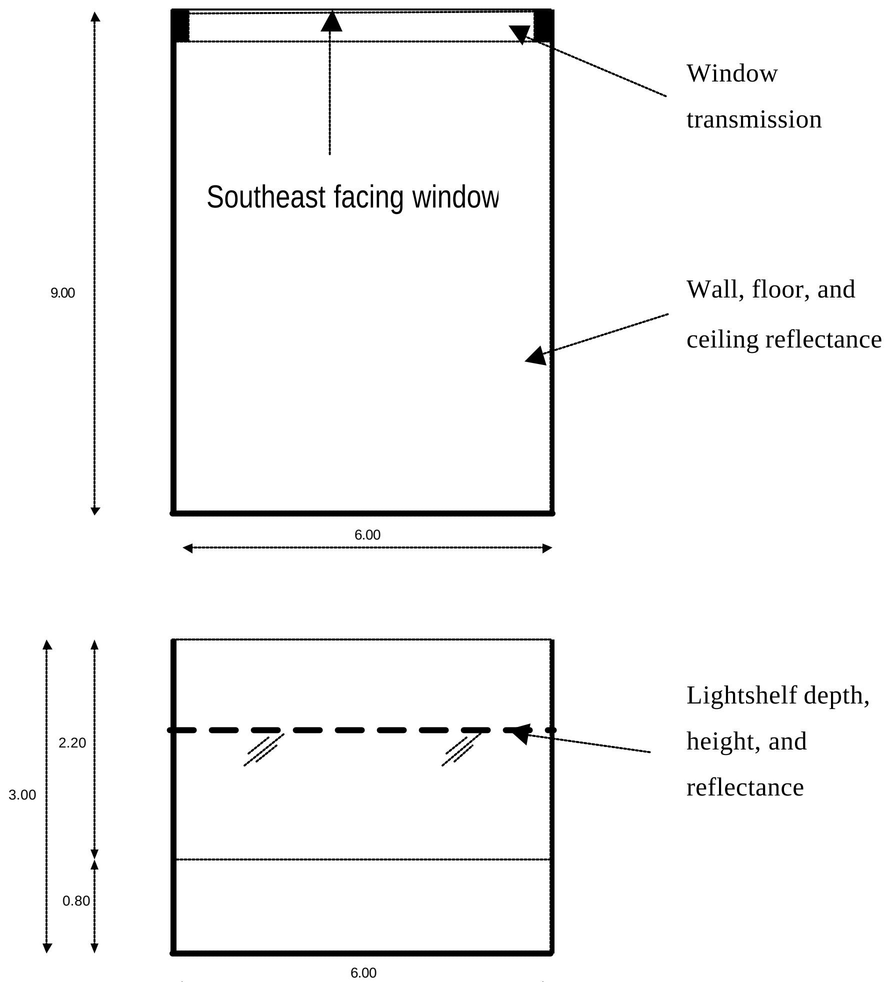
- If there is direct sunlight striking a working surface, the patch of direct sunlight should not be too large and too long. Estimated time is about 15 minutes and a patch of less than the width of the computer screen.
- Workers prefer source of natural light from the side rather than front, back, or top to avoid glare problem on their computer screens.
- The teaming space will need an embedded video camera, embedded speakers, and an embedded microphone for long distance conferencing. Someone should be able to have a video/audio teleconference with others. Lighting conditions should enhance this communication by reducing ambient lighting level.
- The person should be able to view information and interact with that information (e.g. via a computer screen or writing task). The space should provide just enough light for these tasks.
- When someone is using the space, the space should not be blocked from daylight and view outside.
- The space or layout should allow for semi-private interaction and information retrieval with coworker if someone is in the room but not sitting too close.
- The space/furniture arrangement should be as efficient and flexible as possible so that when it is not in use it is out of the way and when it is in need, it is available.
- Wires should be hidden out of sight and circulation within the mechanism.
- Multiple people in the workplace should be able to communicate as well as generate knowledge within its database.
- The space should provide multiple functions for those who are not using the space as an individual workspace. When not in use, the space can be used as a small meeting area, common area, educational station, or as a fun space.

The goal was set to improve lighting condition in the space by eliminating the direct sunlight on the work plane while maintain adequate light levels. The objective function was derived from the users' preferences and these values differ from those used to evaluate other cases. Figure 9.1, 9.2, and 9.3 show different images relative to the existing configuration and its performance. It is assumed to be on the first floor facing southeast with ground reflectance value of 12%. The existing wall, floor, and ceiling reflectance, and window transmission assumed are 50%, 20%, 80%, and 40%, respectively.



IBM new workplace plan
The square is the area of study.

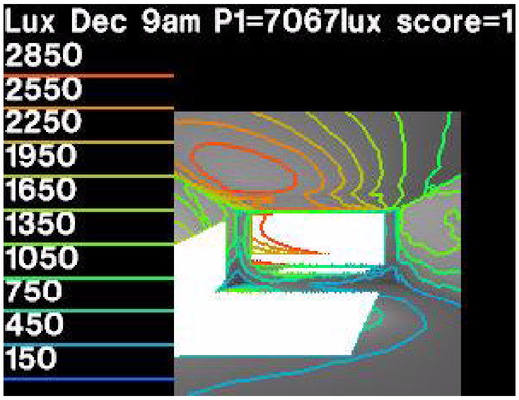
Toronto, Canada



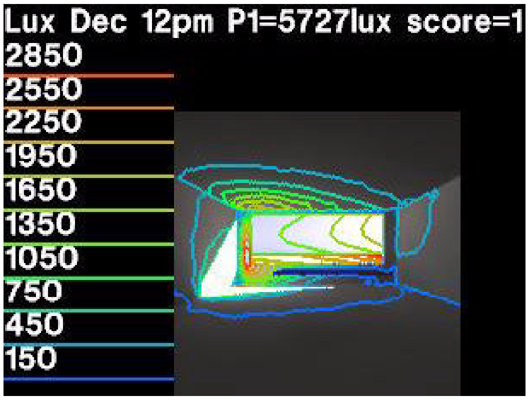
Design Strategy and Variables

Variable1 = lightshelf depth
Variable2 = lightshelf height
Variable3 = lightshelf transmission
Variable4 = wall reflectance
Variable5 = floor reflectance
Variable6 = ceiling reflectance
Variable7 = window transmission

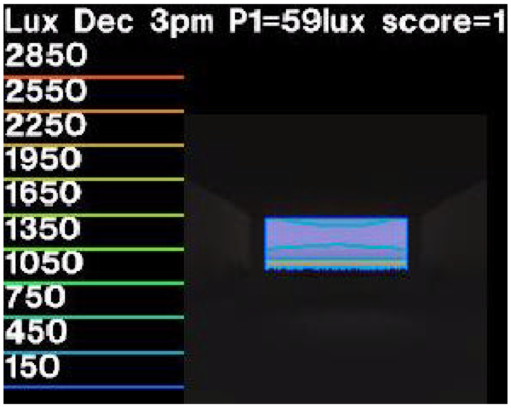
FIGURE 9.1 PLANS AND SECTION OF THE WORKPLACE



Winter 9 AM (Front View)

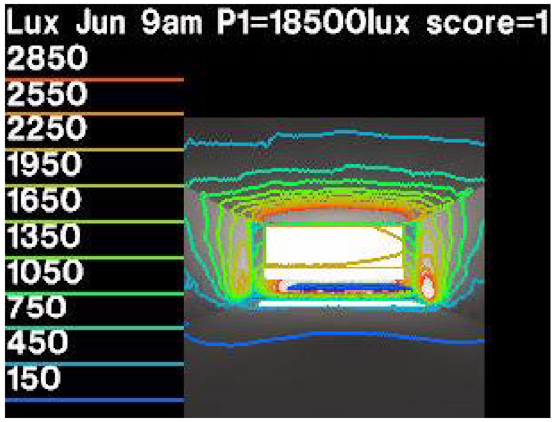


Winter 12 PM (Front View)

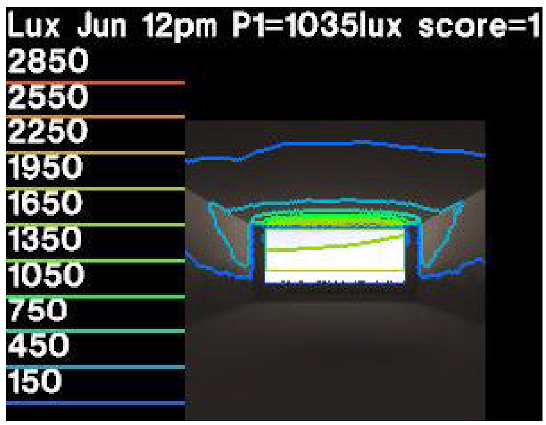


Winter 3 PM (Front View)

FIGURE 9.2 EXISTING LIGHTING CONDITION IN THE WORKPLACE IN THE WINTER GENERATED WITH RADIANCE. POINT 1 IS LOCATED ON THE CENTER OF THE ROOM AT 2.5 FEET ABOVE THE FLOOR.



Summer 9 AM (Front View)



Summer 12 PM (Front View)

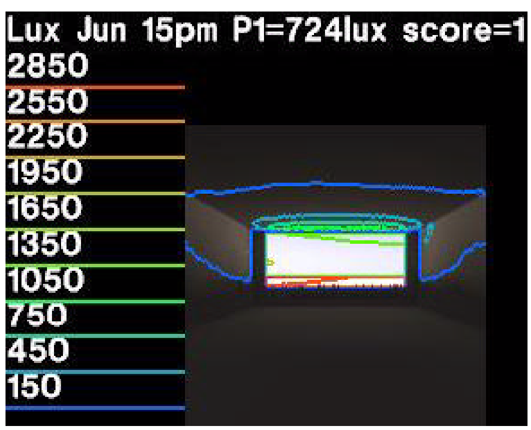


FIGURE 9.3 EXISTING LIGHTING CONDITION IN THE WORKPLACE IN THE SUMMER GENERATED WITH RADIANCE. POINT 1 IS LOCATED ON THE CENTER OF THE ROOM AT 2.5 FEET ABOVE THE FLOOR.

Model and Simulations

The light level performance on the work plane for all seasons is set between 30 to 60 footcandles (323 to 646 lux) as shown in Figure 9.4. If there is direct sunlight on the work plane, penalties have been applied. The building design is controlled by its existing geometry, limiting redesign options. With this limitation in mind, the optimization included only lightshelf depth, height, reflectance, wall, floor, and ceiling reflectance as well as window transmission. The sensor location is in the center of the space on a typical work plane height.

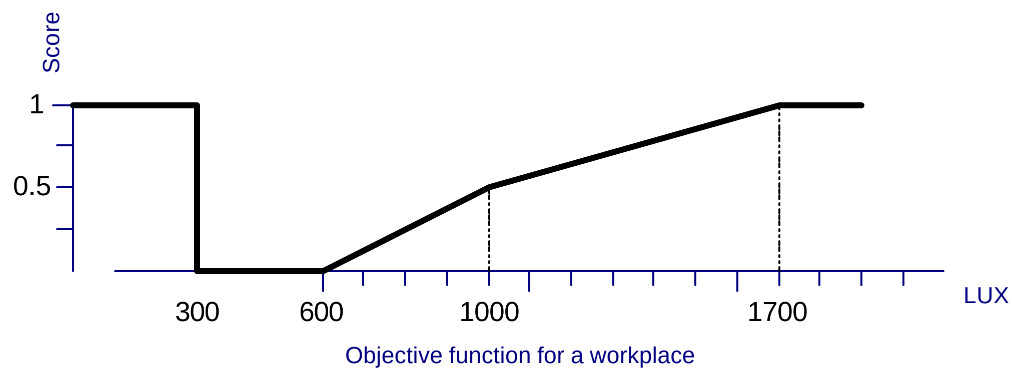


FIGURE 9.4 OBJECTIVE FUNCTION USED IN THIS STUDY

The system is to find solutions for the summer and winter at 9am, 12pm, and 15pm that satisfy the above target. The design variables, constraints, and steps are listed below (m).

TABLE 9.1 DESIGN VARIABLES FOR THE WORKPLACE

Variables	Minimum	Maximum	Step
1.Lightshelf depth	0.5	2.2	0.20
2.Lightshelf height	1.5	2.9	0.20
3.Lightshelf reflectance	0.3	0.8	0.1
4.Wall reflectance	0.3	0.8	0.1
5.Floor reflectance	0.3	0.8	0.1
6.Ceiling reflectance	0.3	0.8	0.1
7.Window transmission	0.1	0.8	0.1

From studies on GA parameters in this thesis, GA parameters used in this chapter are:

Population size	= 20	Number of generations	= 10
Crossover rate	= 0.9	Mutation rate	= 0.01

Results

As the system evolves, it is obvious that the patterns of genomes indicate the significant role of lightshelf height for the summer season. It should be placed as high as possible. Because the space has southeast–facing window, there is an adequate amount of light within the space without using lightshelf. The need, in this case, is to avoid direct sunlight that provides unwanted glare. Therefore, the reflectance of the lightshelf does not matter, since it is placed at the highest location on the window (2.9m). Wall and floor reflectance should be about 60% to 70%, which is high enough to provide ambient light level. Moreover, from the results presented in Figure 9.5 and 9.6, the ceiling reflectance should be as low as possible (30%), due to the bright reflectivity from the sun striking the ground during summer. Source of light within the space in the summer is largely from the ground instead of the sky.

As shown in Figure 9.5, each chromosome represents a set of room or variable configurations. Each gene represents optimized values assigned by GA. During the evolving process, the designer can choose output option to view the quality and quantity of the optimized solutions for each iteration or generation. It can be the best solution, the third best solutions, or any numbers at anytime of day or year. The system displays the optimized values along with their rendering images such that the designer could learn pattern and characteristic of the solutions given by GA. Figure 9.5 is an abstract that shows how GA allocates values from the first generation to the last generation for this particular problem.

Figure 9.7 compares daylighting performance of the space before and after being optimized in December. As mentioned above, the objective is to maintain preferred lighting levels on the work plane in the center of the room. The GA has not found a solution that satisfies all the requirements. However, it assigned the best design option for the particular time as presented in Figure 9.7. The lightshelf is low and wide enough to provide shade on the work plane at 9.00am, while maintaining appropriate lighting level at 12.00pm and 3.00pm. Though, the result might not be practical because the lighting distribution in the space needs to be taken care in both vertical and horizontal planes throughout the working surfaces, instead of one point or surface. This is rather time-consuming and falls short of the aims of the tool to allow the easy manipulation of the model. Future work on this issue is in critical need.

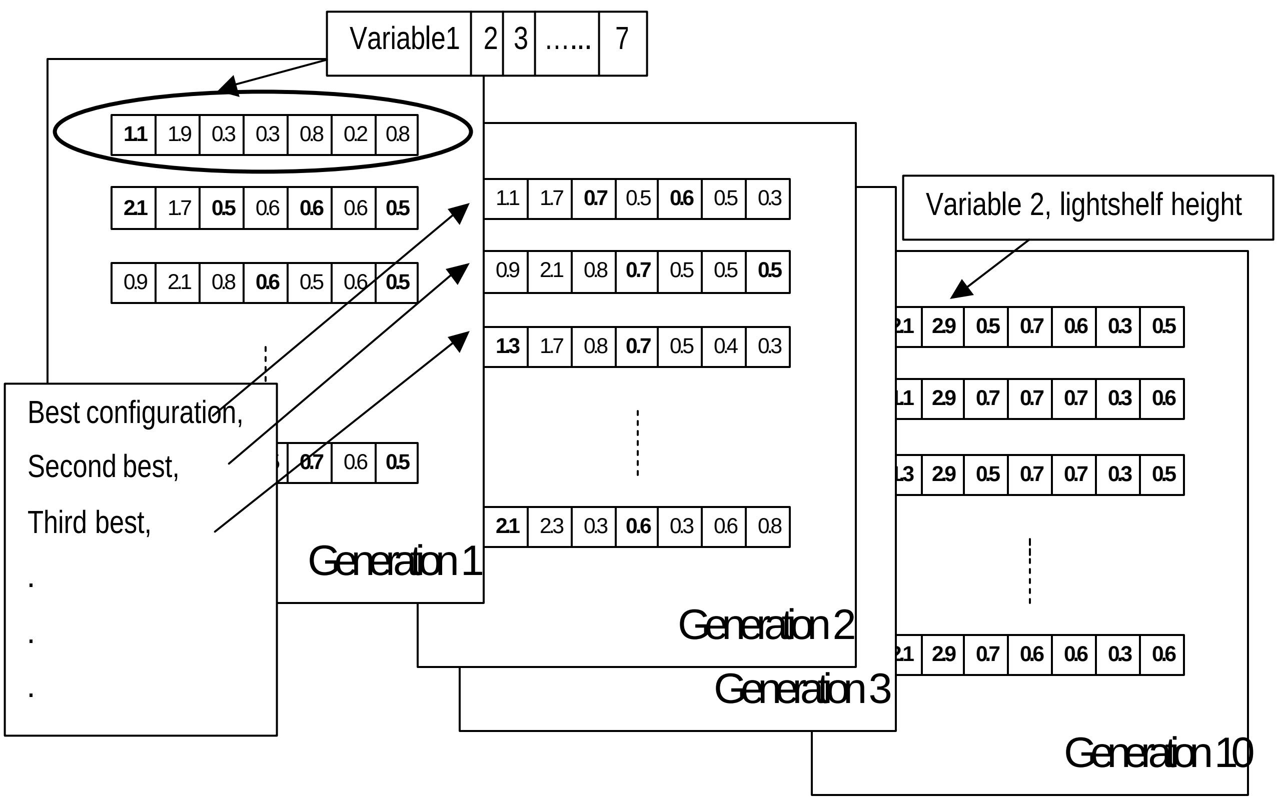
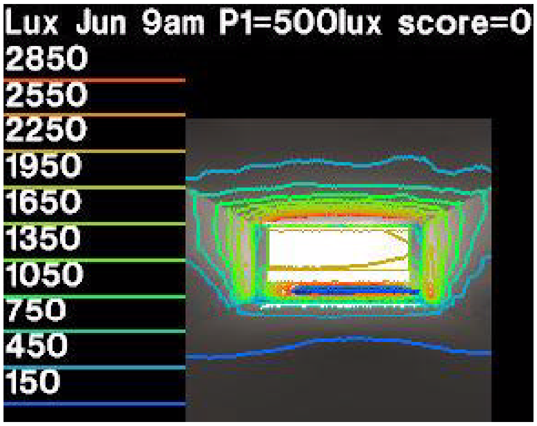
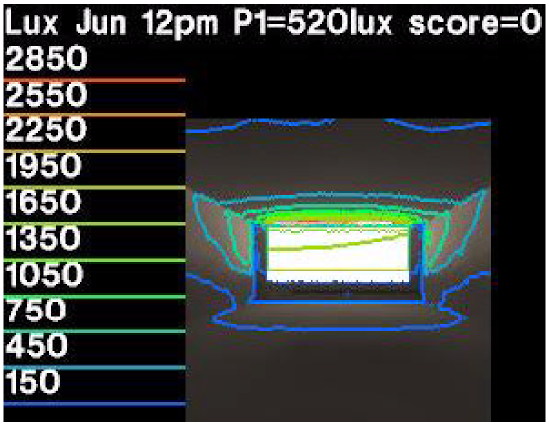


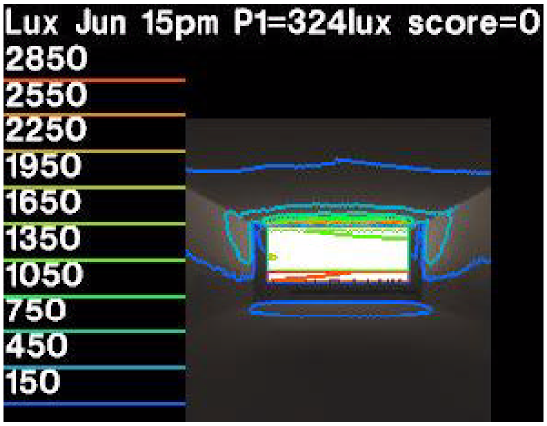
FIGURE 9.5 EXAMPLE OF AN EVOLVING REPRESENTATION FROM THE FIRST GENERATION TO THE LAST GENERATION. THE BOLD NUMBERS DENOTED EVOLVED GENES.



Summer 9 AM Optimized solution



Summer 12 PM Optimized solution



Summer 3 PM Optimized solution

FIGURE 9.6 LIGHTING CONDITION IN THE OPTIMIZED SPACE. LIGHTSHELF IS ASSIGNED AT 2.9' ABOVE THE FLOOR AT THE TOP OF THE WINDOW. THEREFORE, IT CAN NOT BE SEEN IN THE RENDERINGS. POINT 1 IS LOCATED AT THE CENTER OF THE ROOM ON A DESK 2.5 FEET ABOVE THE FLOOR.

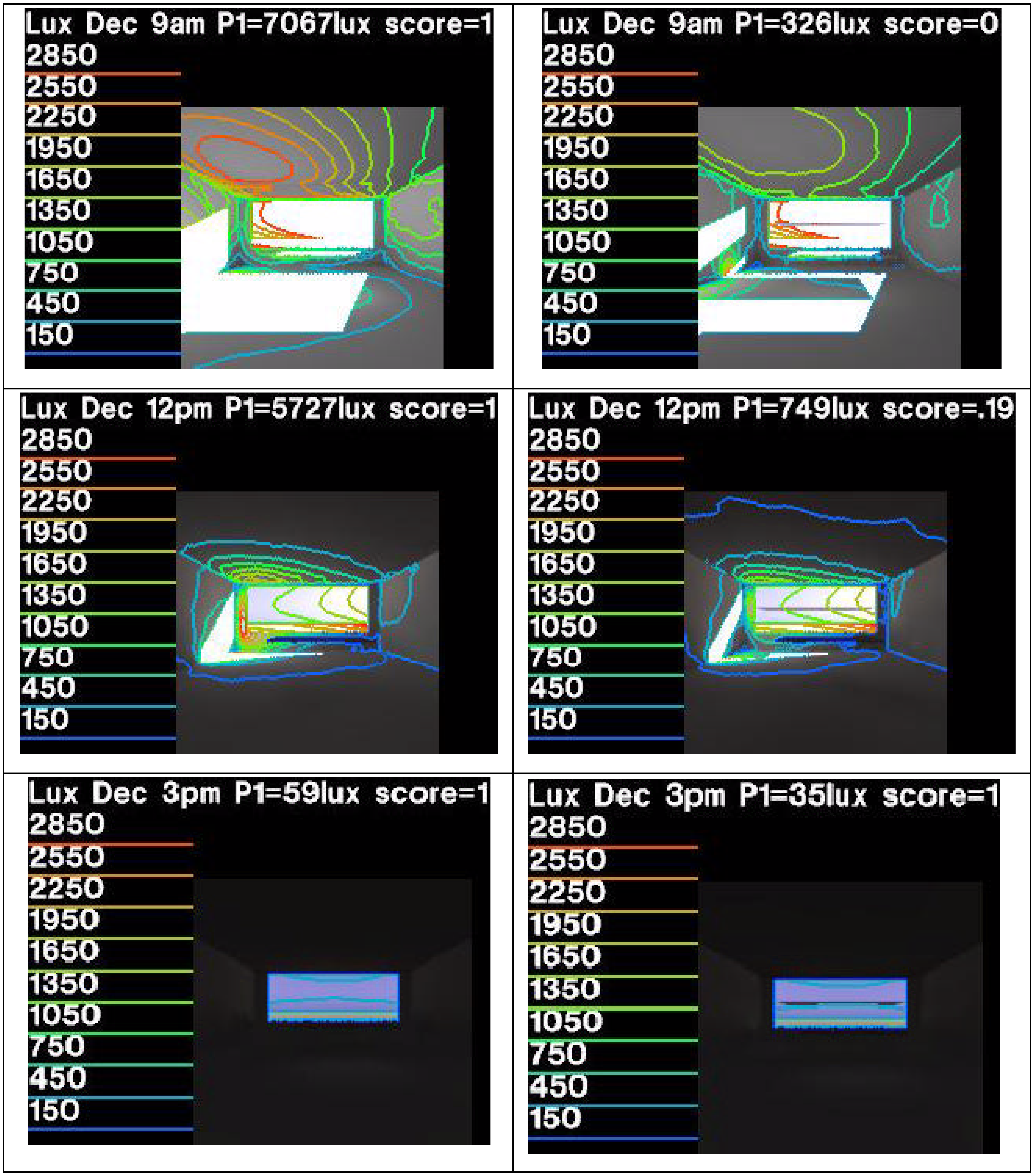


FIGURE 9.7 LIGHTING CONDITION IN DECEMBER BEFORE (LEFT COLUMN) AND AFTER (RIGHT COLUMN) BEING OPTIMIZED. POINT 1 IS LOCATED AT THE CENTER OF THE ROOM AT 2.5 FEET ABOVE THE FLOOR.

9.2 Wexner Center for Visual Arts, Columbus, Ohio

The second example, the Wexner Center designed by architect Peter Eisenman, is a center for visual art and a museum at Ohio State University, which is currently undergoing lighting reevaluation. The university utilizes The Wexner Center for artwork from paintings to sculpture. The gallery does not possess reconfigurable elements that would help to accommodate disparate artwork requirements. Consequently, the center suffers from too much daylight for paintings, although the light level is adequate for sculpture, shown graphically in Table 9.3, Figure 9.8, and 9.9. Bold numbers in Table 9.3 denote illuminance levels that are much greater than recommended level shown in Table 9.2.

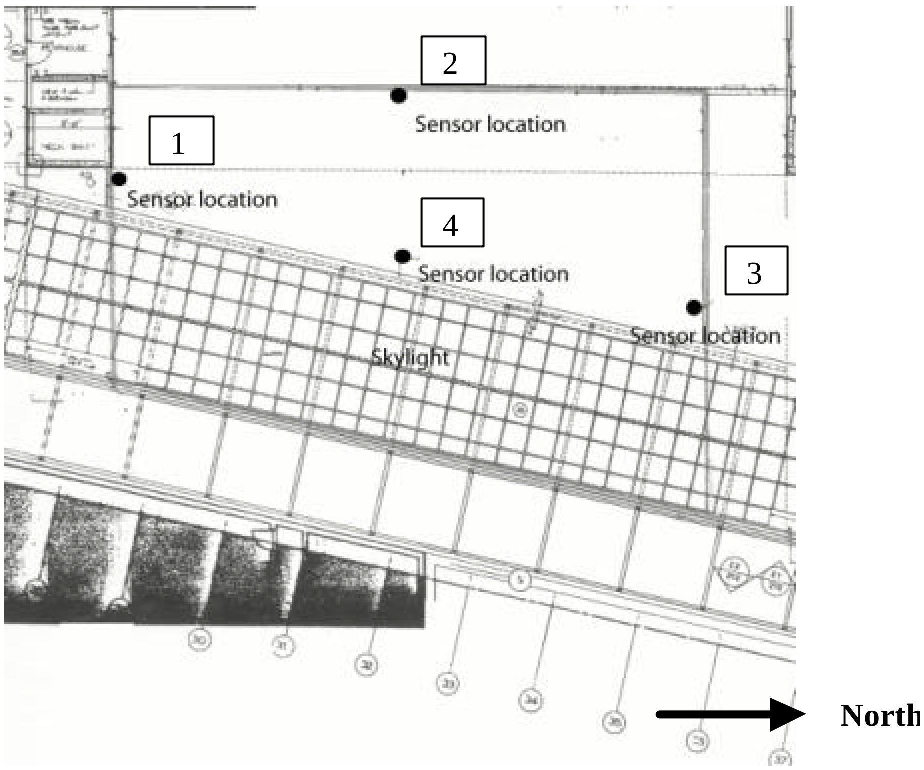
TABLE 9.2 RECOMMENDED LIGHTING LEVEL BY THE IESNA

Application	Lux	Footcandles
Ambient lighting	50 to 300	5 to 30
Text panels	100 to 300	10 to 30
Controls	100	10
Directional signage	200 to 300	20 to 30
Ramps, stairs	100 to 300	10 to 30
Visitor pathways	100 to 300	10 to 30

TABLE 9.3 EXISTING DAYLIGHTING GENERATED WITH RADIANCE

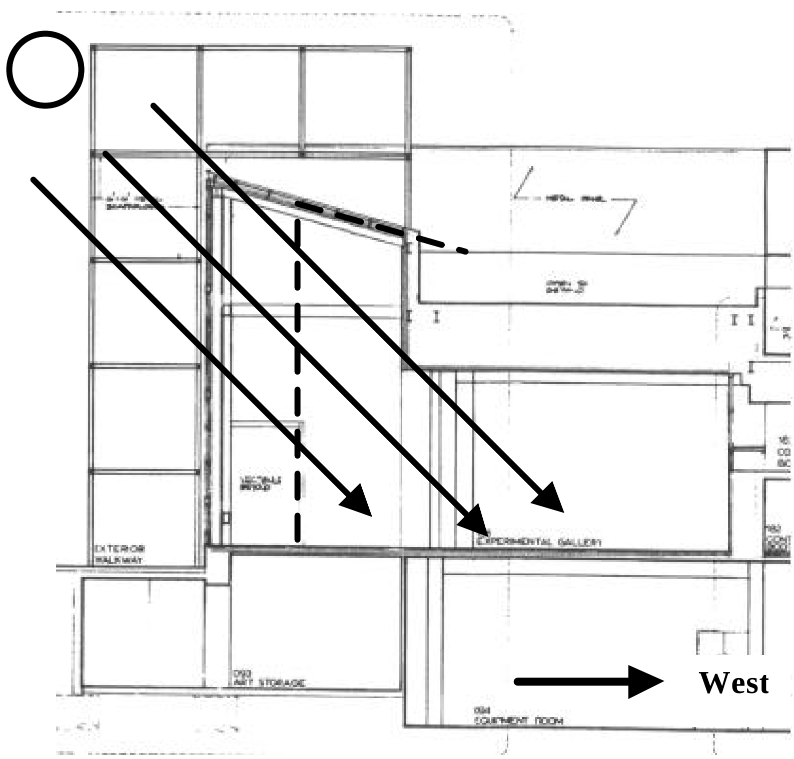
Based on 10% transmission for glass, 40% for skylight

	Winter (lux)			Summer (lux)		
	9am	12pm	15pm	9am	12pm	15pm
Point 1-Vertical surface on the south wall	108	183	32	**581**	**667**	269
Point 2-Vertical surface on the west wall	118	75	11	**312**	**334**	**355**
Point 3-Vertical surface on the north wall	**2927**	291	22	**1162**	**850**	226
Point 4-Horizontal surface on the floor	97	226	43	**398**	**667**	**334**



The Wexner Center for Visual Arts Plan

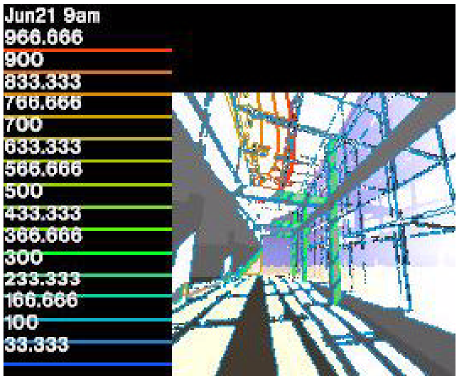
Columbus, Ohio



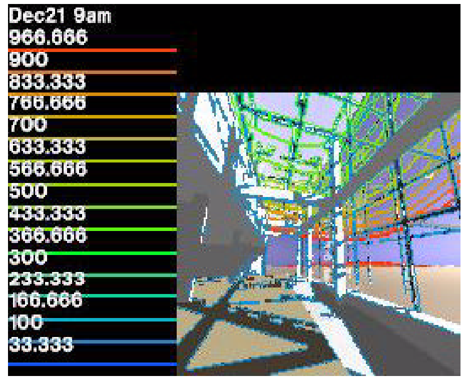
Design Strategy and Variables

Variable1 = fabric transmission for east facade
Variable2 = fabric transmission for skylight

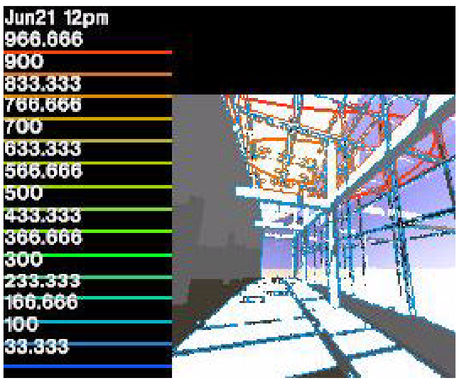
FIGURE 9.8 WEXNER CENTER FIRST FLOOR PLAN AND SECTION



Summer 9 AM

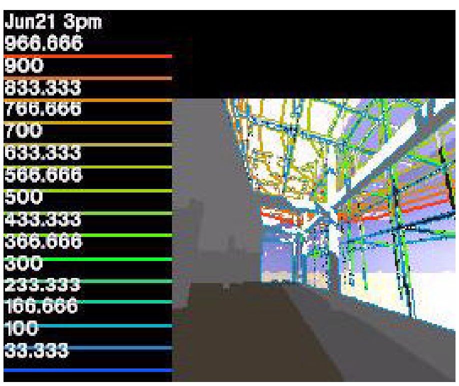


Winter 9 AM

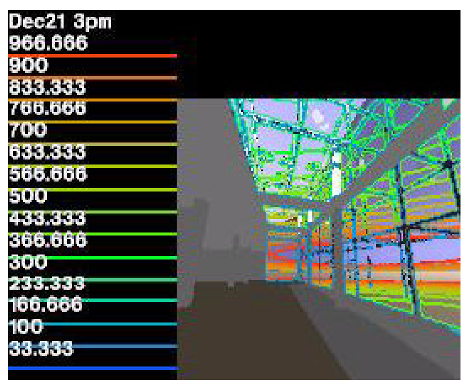


Summer 12 PM

Winter 12 PM



Summer 3 PM



Winter 3 PM

FIGURE 9.9 EXISTING DAYLIGHTING CONDITION IN THE WEXNER CENTER FOR VISUAL ARTS

Model and Simulations

The owner's preference is the flexibility of the gallery throughout the year with introducing reconfigurable skylight and window transmissions. Thus, the intent was to consider modifications that would improve the lighting conditions as a whole for different times of year. Unlike the optimization of IBM building, which included material changes as well as geometry optimization, here it is restricted exclusively to material changes since the owner would like to preserve Eisenman's grid systems. The existing wall, floor, ceiling reflectance as well as window and skylight transmission are 50%, 20%, 80%, 10%, and 40% respectively. Window transmission was measured by the designer at the site but the skylight transmission is an approximate number.

The light level for artwork recommended by the IESNA falls between 100 to 300 lux. This goal was specified in the objective function to include four measurement points in the space, equally weighted as shown in Figure 9.10. Point 1, 2, and 3 are vertical positions at a human's eye level, where point 4 is positioned on the floor. The lighting designer's strategy is to use fabric and/or motorized louvers inside the building to filter daylight.

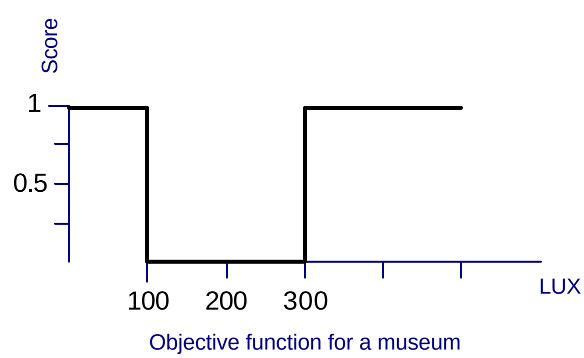


FIGURE 9.10 OBJECTIVE FUNCTION FOR THE WEXNER CENTER USED IN THIS STUDY

The system is to find solutions for the summer and winter at 9am, 12pm, and 15pm that satisfy the above target. The design variables, constraints, and steps are listed below.

TABLE 9.4 DESIGN VARIABLES FOR THE MUSEUM

Variables	Minimum	Maximum	Step
1.Fabric transmission for east facade	0	0.95	0.05
2.Fabric transmission for skylight	0	0.95	0.05

Results

To study the roles of toplight, sidelight and their effectiveness, the optimization was conducted for three different latitudes: Columbus, Ohio; Helsinki, Finland; and Bangkok, Thailand. From experiencing using this design tool, I have learned patterns that GA has assigned for each variable from those small and multiple images as shown in Figure 9.10 as an example. Table 9.5 summarizes the optimized solutions.

TABLE 9.5 SUMMARY OF THE OPTIMIZED SOLUTIONS FOR THE WEXNER CENTER FOR DIFFERENT CLIMATES

Columbus, Ohio	Winter (%transmission)			Summer (%transmission)		
	9am	12pm	15pm	9am	12pm	15pm
Shading device transmission for window	30to40	75	60to75	20	35to85	45to70
Shading device transmission for skylight	20to70	10to15	50to60	10	5	5to15

Helsinki, Finland	Winter (%transmission)			Summer (%transmission)		
	9am	12pm	15pm	9am	12pm	15pm
Shading device transmission for window	100	100	100	18	34to36	62
Shading device transmission for skylight	100	100	100	8	12	18to20

Bangkok, Thailand	Winter (%transmission)			Summer (%transmission)		
	9am	12pm	15pm	9am	12pm	15pm
Shading device transmission for window	18	22	50to56	30	73to83	63
Shading device transmission for skylight	6	12	6	5	10to13	15

The optimization took 8 to 12 minutes to converge. There are too many images to be included in this thesis. Figure 9.10 is an example of the output from the tool that the designer could view throughout the design process. Quality of images appeared in Figure 9.10 could be improved by using accurate rendering option in Radiance. However, it could take time more than double in order to converge. The pattern of the results in Figure 9.11 and 9.12 indicates that a shading device for the east window plays an important role in the morning since the sun angle is lowest. As shown in Figure 9.12, GA assigned the transmission of the east window at 9.00am in the winter to be about 30% to 40%, which provides enough illuminance level on the east and north walls and maintains the light level to be lower than 300 lux. Later times of day, it should be opened as much as possible (Figure 9.12).

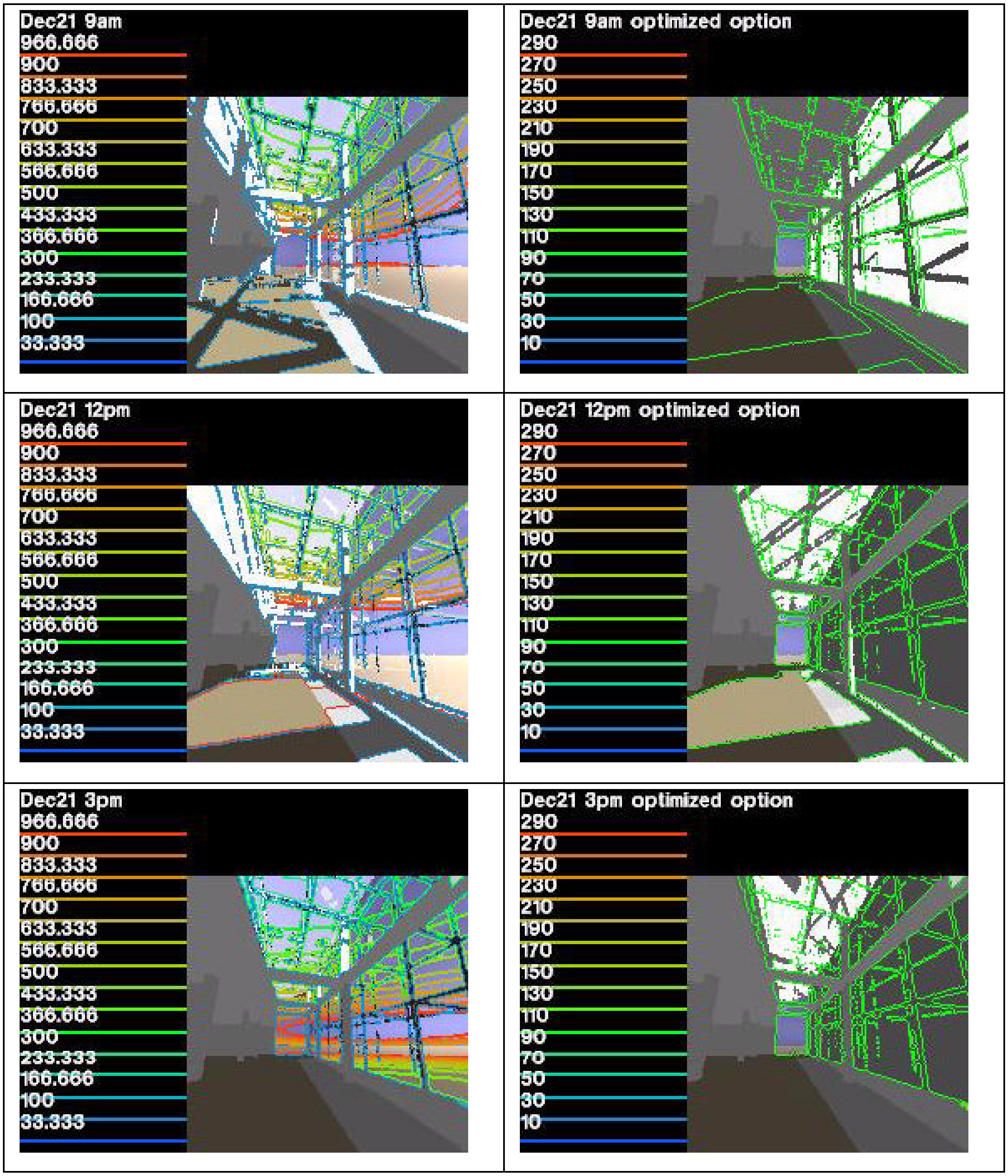


FIGURE 9.10 COMPARISONS OF THE LIGHTING PERFORMANCE IN THE GALLERY THROUGHOUT THE DAY IN DECEMBER BEFORE (LEFT COLUMN) AND AFTER (RIGHT COLUMN) BEING OPTIMIZED.

In contrast, the shading device for the skylight should block the sun for most of the year. The system assigned lower transmission material for the east side in the morning and higher transmission for noon and afternoon. The motorized louver may be considered for the east window for flexibility purposes as well as to provide ambient light from the sky in the afternoon. It is interesting to note that although daylight availability for the winter is not adequate or less than 100 lux, the system still assigned fabric transmittance of 50% to 60% for the skylight. The illuminance levels of the space with the fabric are greater than those without any fabric applied. This phenomenon indicates that when the sun is at a lower angle with lower lighting intensity, the use of diffuse material for the skylight helps improving the ambient light level by bringing more light into the space. Figure 9.13 illustrates this concept.

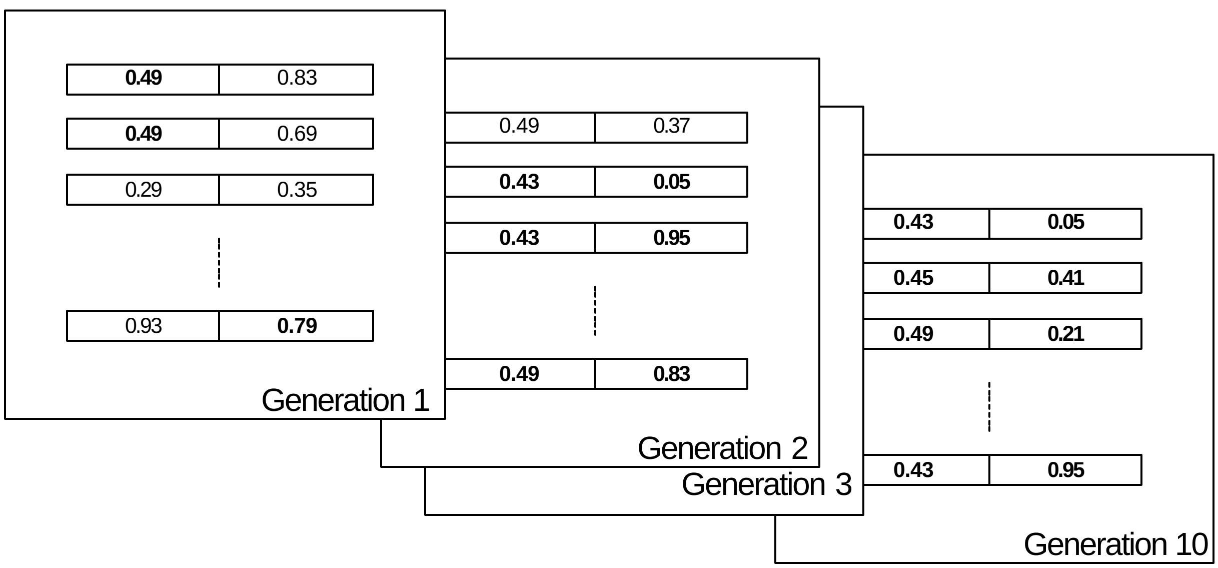


FIGURE 9.11 AN EVOLVING REPRESENTATION FROM THE FIRST GENERATION TO THE LAST GENERATION FOR THE WINTER SEASON AT 9AM IN OHIO. THE BOLD NUMBERS DENOTED EVOLVED GENES.

Winter 9 (lux)					
V0=0.43	V1=0.05	x1=130.544	x2=130.868	x3=175.641	x4=168.629
V0=0.43	V1=0.39	x1=131.249	x2=130.868	x3=176.071	x4=171.957
V0=0.49	V1=0.21	x1=144.728	x2=164.728	x3=199.919	x4=199.288
V0=0.43	V1=0.95	x1=132.41	x2=130.869	x3=176.779	x4=177.44
V0=0.43	V1=0.83	x1=132.161	x2=130.869	x3=176.628	x4=176.265
Winter 12 (lux)					
V0=0.05	V1=0.15	x1=92.8607	x2=13.5646	x3=45.701	x4=201.185
V0=0.45	V1=0.63	x1=277.733	x2=44.8124	x3=170.268	x4=817.787
V0=0.43	V1=0.05	x1=81.6902	x2=21.9237	x3=33.3061	x4=92.053
V0=0.37	V1=0.31	x1=154.18	x2=30.168	x3=92.4113	x4=415.022
V0=0.95	V1=0.39	x1=218.805	x2=76.4648	x3=129.737	x4=538.484
Winter 15 (lux)					
V0=0.51	V1=0.63	x1=73.5459	x2=12.635	x3=62.4643	x4=241.479
V0=0.83	V1=0.41	x1=52.2452	x2=12.6057	x3=45.6212	x4=161.706
V0=0.69	V1=0.79	x1=90.98	x2=15.809	x3=78.3145	x4=303.12
V0=0.73	V1=0.79	x1=91.1738	x2=16.1212	x3=78.6636	x4=303.473
Summer 9 (lux)					
V0=0.03	V1=0.23	x1=147.445	x2=22.0535	x3=99.2309	x4=519.555
V0=0.39	V1=0.11	x1=155.571	x2=173.762	x3=233.28	x4=389.186
V0=0.13	V1=0.15	x1=115.802	x2=48.6017	x3=115.972	x4=348.47
V0=0.49	V1=0.09	x1=170.232	x2=152.448	x3=258.915	x4=407.322
V0=0.21	V1=0.09	x1=104.288	x2=71.02	x3=127.669	x4=272.312
Summer 12 (lux)					
V0=0.33	V1=0.13	x1=177.497	x2=38.0591	x3=170.672	x4=682.767
V0=0.33	V1=0.05	x1=80.6247	x2=25.6796	x3=89.202	x4=278.621
V0=0.09	V1=0.13	x1=169.412	x2=25.7231	x3=153.69	x4=665.417
V0=0.85	V1=0.05	x1=96.03	x2=52.6218	x3=126.373	x4=315.757
V0=0.63	V1=0.05	x1=89.5027	x2=41.1827	x3=110.646	x4=300.018
Summer 15 (lux)					
V0=0.47	V1=0.05	x1=76.8352	x2=39.433	x3=77.1821	x4=249.409
V0=0.67	V1=0.09	x1=122.001	x2=57.9474	x3=138.807	x4=436.099
V0=0.17	V1=0.09	x1=110.786	x2=24.2821	x3=113.35	x4=407.861
V0=0.47	V1=0.15	x1=202.034	x2=51.3411	x3=197.918	x4=690.176
V0=0.67	V1=0.05	x1=81.6301	x2=53.1841	x3=87.351	x4=260.913

Design solutions and performance

V0=fabric transmission for east façade
V1=fabric transmission for skylight
X1=illuminance level at point1
X2= illuminance level at point2
X3= illuminance level at point3
X4= illuminance level at point4

FIGURE 9.12 EXAMPLE OF THE SOLUTION PATTERNS FOR THE COLUMBUS CASE GENERATED DURING THE EVOLVING PROCESS THAT THE DESIGNER CAN LEARN FROM.

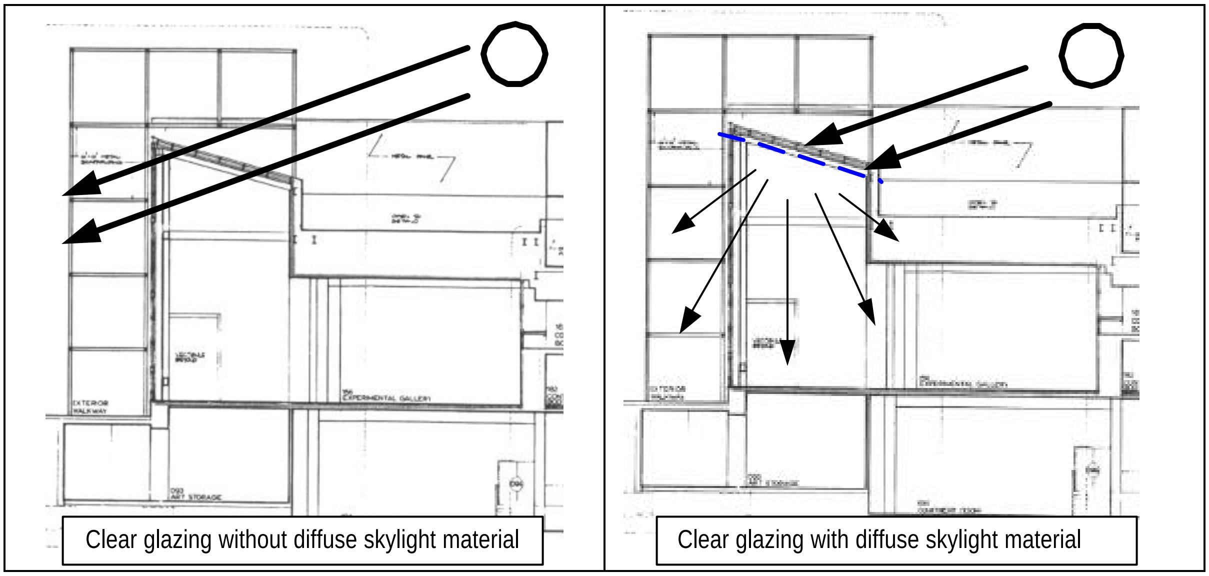


FIGURE 9.13 THE USE OF DIFFUSE MATERIAL THAT IMPROVES LIGHTING DISTRIBUTION INTO THE SPACE.

In the second case, the location is switched to a higher altitude site, Helsinki, Finland. The sun angles are low most of the year. There is no solution for the winter season since the daylight availability is way too low because the sun has not risen yet or at its lower position. Therefore, any solution does not make any difference. For the summer, the effect is very much the same as those of the previous case. The last example is located in Bangkok, Thailand, which the sun position is high throughout the year. The solutions are as expected since I have learned from the previous projects. However, it is hard to find the solutions since the daylight availability in Bangkok is too much for the museum with a skylight and single glazing façade. The system found the solutions in the last generation, compared to the previous cases, which have converged within 4 to 6 generations.

This time, a new initializer has been created in order to generate better genomes that will help the system to converge faster. It is customized such that the designer could input any preferred initial configurations based on available knowledge. For this test, four genomes out of twenty contained evolved genes. The result is that the system has converged within generation 3, which is about 60% faster. This informs that the tool that has a feature to incorporate better genomes in initial population will help improving design quality and time.

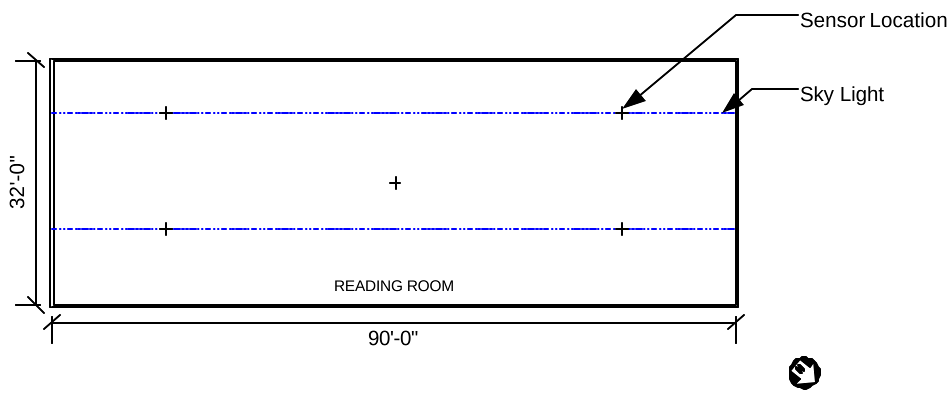
9.3 A Public Library, Albany, New York

The third example is a public library in Albany, New York. The space is designed to accommodate reading activity. The existing wall, floor, ceiling reflectance and skylight transmission are 50%, 20%, 80%, and 15% respectively. The skylight is located in the center of the space and the five measurement locations are placed in the reading area as shown in plan illustrated below in Figure 9.14. There is a serious problem with unwanted heat and glare. Average light levels and existing conditions are presented in Figure 9.15. There are excessive lighting levels throughout the day.

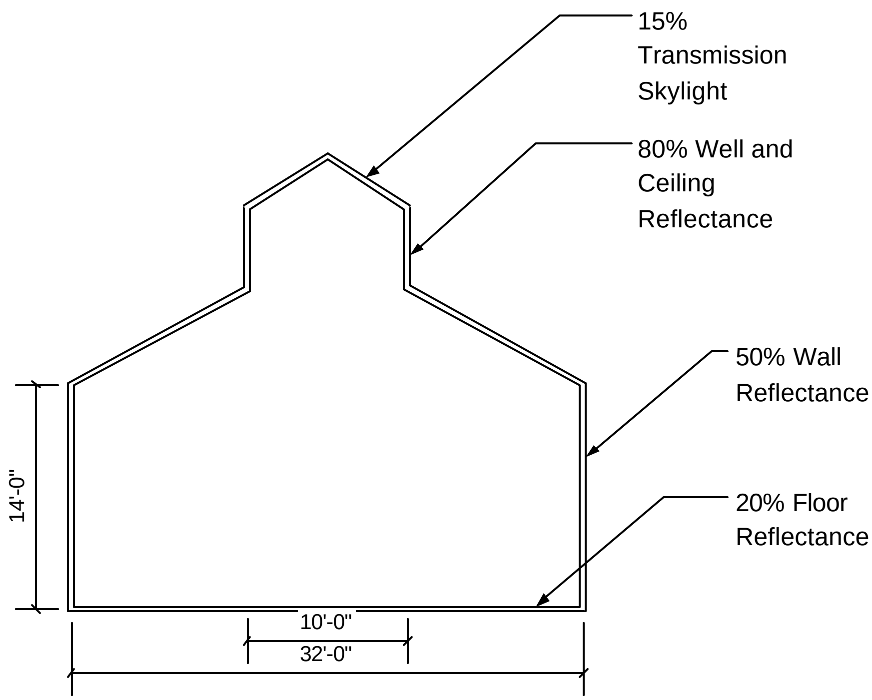
This study was conducted to compare with a physical model generated and measured by a lighting designer and me. The process began with building the model. Then the designer took an initial guess. We then built and measured lighting performance on the designer's design schemes under real clear and overcast sky conditions over three seasons using a sundial. Originally, there were 4 designs. Finally, we ended up exploring only two or three options due to time and climate limitations. More detail on this project can be found in Appendix B. This project took 20 days to complete compared to this system, which took 2 days to produce the same results. The simulation part only took 30 minutes.

Model and Simulations

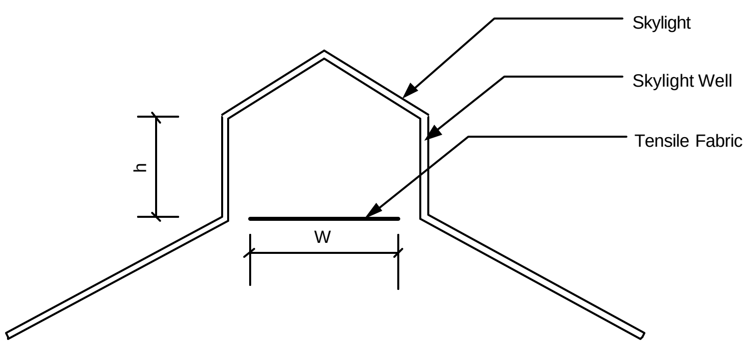
The designer's goal was to provide enough light level for reading activity without allowing too large patches of direct sunlight on the work plane. The light level performance on the work plane for all seasons is set between 40 to 60 footcandles or 430 to 646 lux as shown in Figure 9.16. It was the designer's idea to specify the minimum patch of the sun not to be greater than about 15" for longer than 15 minutes. It is preferred to underlight during summer better than overlight during winter because the heat gain is too great. The shading device should also allow readers in the reading area to see the sky. Thus, the shading device variables are set as presented in table 9.6. The design variables are fabric properties and positions in the skylight well. The sensor locations are indicated in the building plan in which the scores for each location are equally weighted.



A public library plan and five measurement points in the space
Albany, New York



Building Section

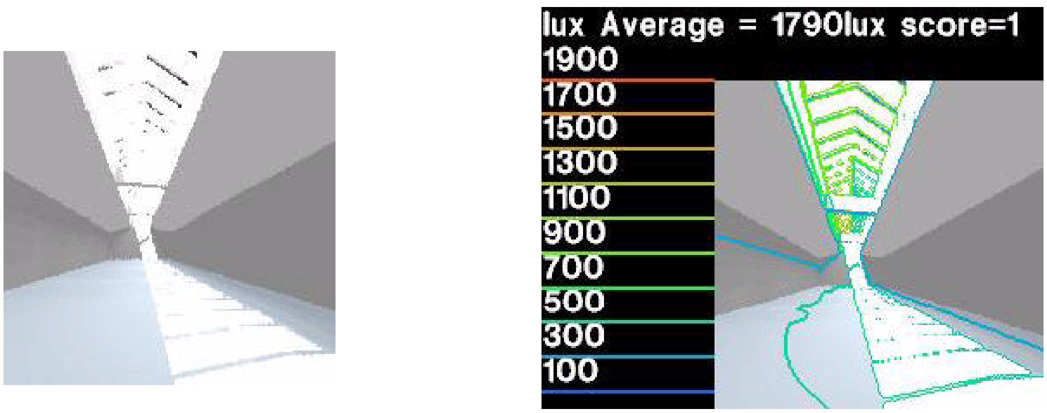


Design strategy and variables

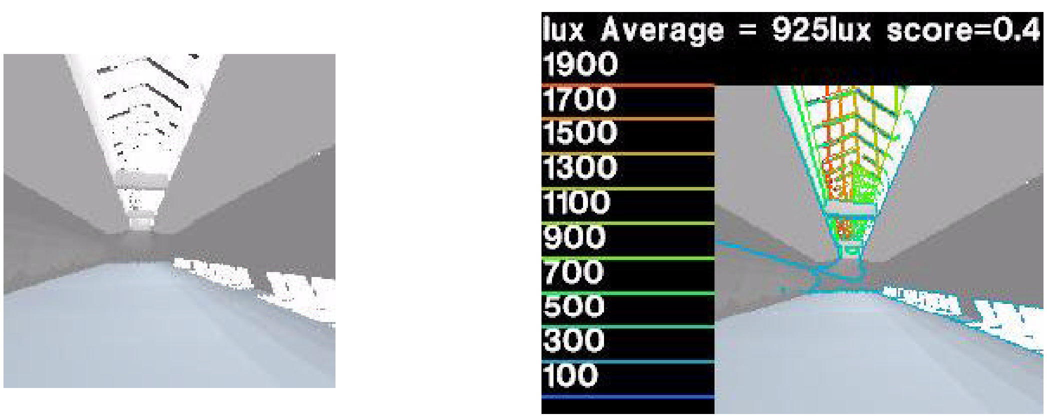
Variable1 = width of the fabric
Variable2 = height of the fabric
Variable3 = fabric transmission

FIGURE 9.14 BUILDING PLAN, SECTION, AND DETAIL, ALBANY, NEW YORK

Summer 9 AM



Summer 12 PM



Summer 3 PM

FIGURE 9.15 EXISTING DAYLIGHTING CONDITION IN A PUBLIC LIBRARY IN ALBANY, NEW YORK

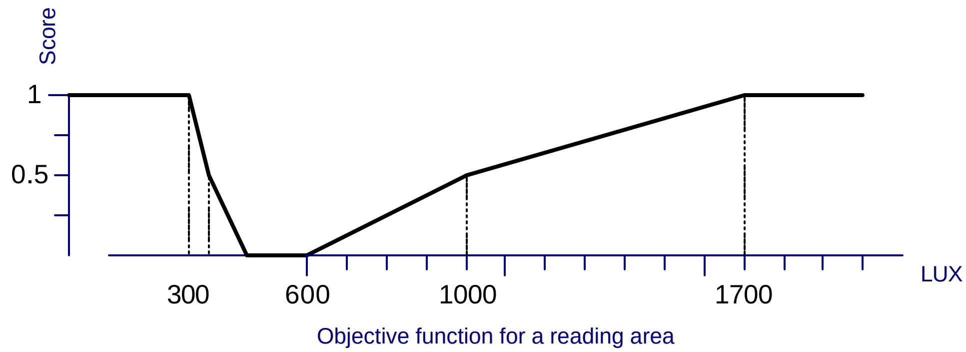


FIGURE 9.16 OBJECTIVE FUNCTION FOR THE LIBRARY, ALBANY, NEW YORK

The system is to find solutions for the summer and winter at 9am, 12pm, and 15pm that satisfy the above target. The design variables, constraints, and steps are listed below (ft).

TABLE 9.6 DESIGN VARIABLES FOR THE LIBRARY

Variables	Minimum	Maximum	Step
1.Fabric width	5	9.5	0.5
2.Fabric height	20	23	0.5
3.Fabric transmission	0.2	0.9	0.05

Results

Before the optimization process took place, lighting levels read from a computer simulation and physical model were compared. The average illuminance values at the five sensor locations of both models are comparable within an acceptable range of 10% error. Therefore, the results found from this system should be very close to what found from the physical model. The system assigned the fabric transmission of 15% to 20% with a width of 8' to 9.5' that can be located at any height along the skylight well. The solutions are very close to what found from the physical model studies that yielded the width of 8' and 20% to 25% fabric transmission.

Figure 9.17 presented below shows that in order to obtain the desired lighting performance, it is important to maintain fabric transmission to 15% to 20%, where the height does not have any effect on the lighting level in the space. The results converged to populations consisting of optimal or near-optimal solutions and the results provide more variation compared to traditional design process. This phenomenon shows that different design configurations may correspond and provide similar environmental performance. This method provides choices of valuable information to the designer, which the designer can then use for further decisions in the design process.

Figure 9.18 and 9.19 present one of the optimized options during winter and summer. The solution allows small patches of the direct sunlight into the space for psychological effect, which is the designer's original intend. However, the system provided more than one solutions that exhibit the same performance. Therefore, the designer could have choices to select from. There is the potential for the tool to involve people or designers who do not have expertise in the lighting design field.

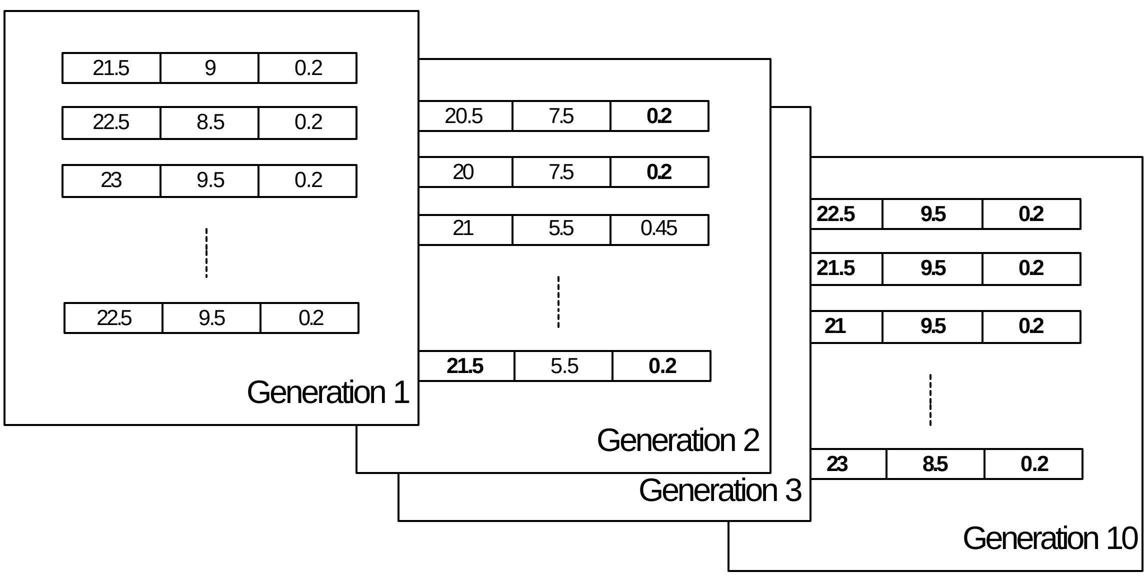
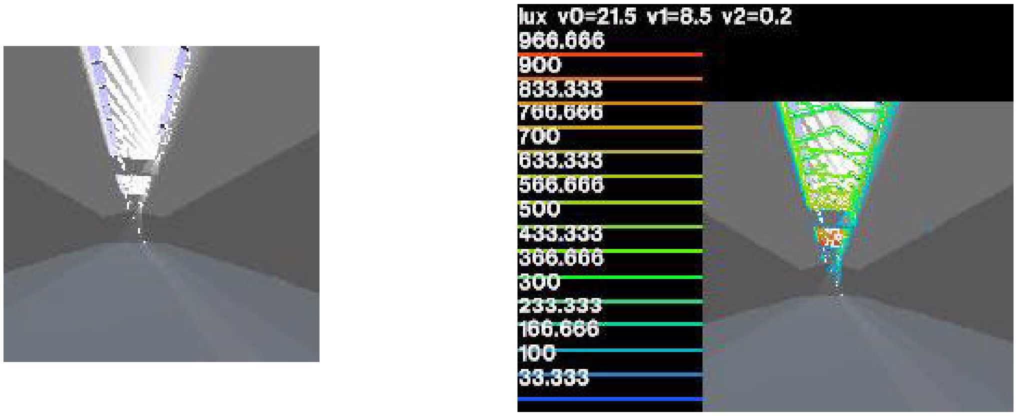
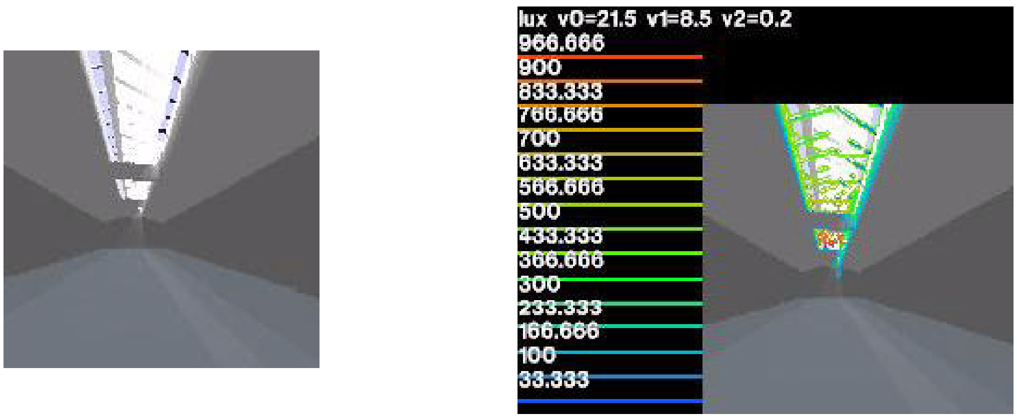


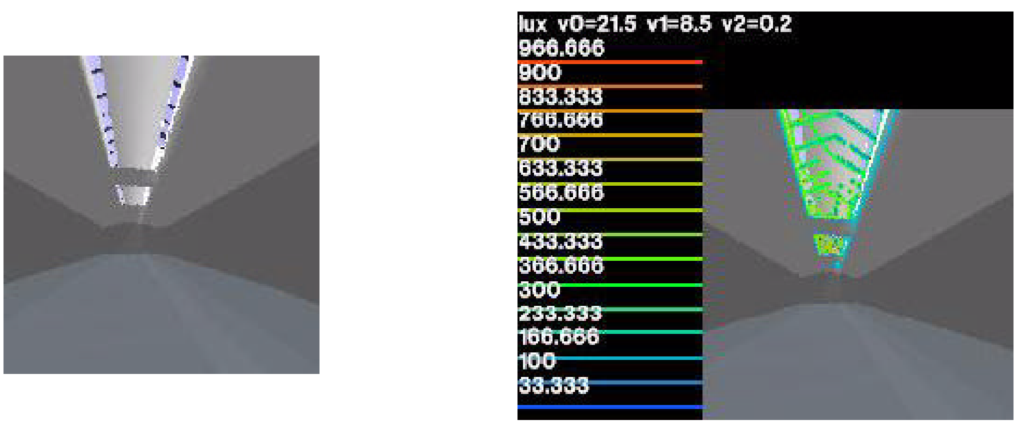
FIGURE 9.17 AN EVOLVING REPRESENTATION FROM THE FIRST GENERATION TO THE LAST GENERATION FOR THE LIBRARY. THE BOLD NUMBERS DENOTED EVOLVED GENES.



Winter 9 AM Optimized solution



Winter 12 PM Optimized solution



Winter 3 PM Optimized solution

FIGURE 9.18 IMPROVED DAYLIGHTING CONDITION IN THE WINTER AFTER BEING OPTIMIZED

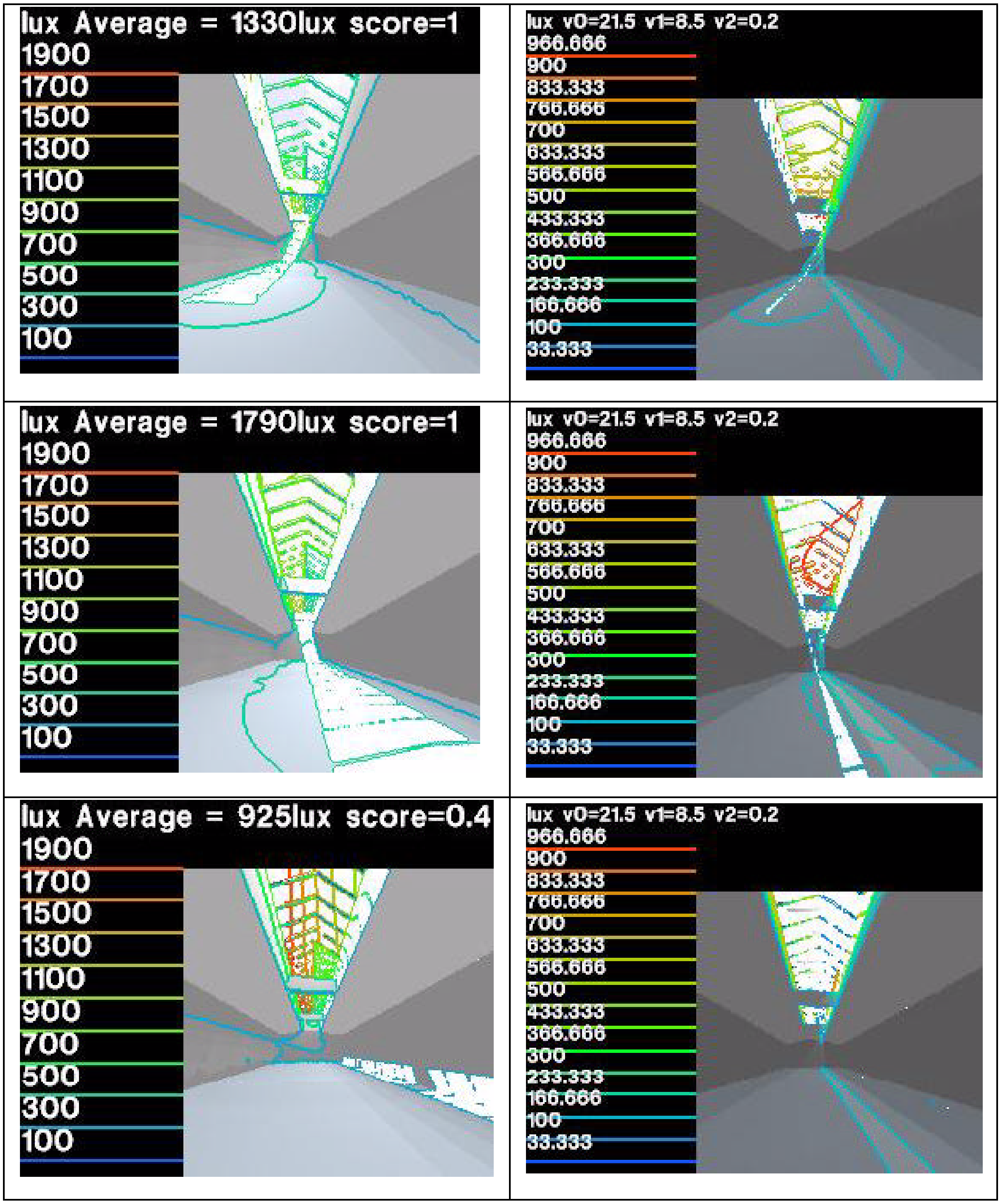


FIGURE 9.19 EXISTING LIGHTING CONDITION (LEFT COLUMN) AT 9.00AM, 12.00PM, AND 15.00PM, COMPARED TO IMPROVED DAYLIGHTING CONDITION (RIGHT COLUMN) IN THE SUMMER.

Chapter X Conclusions and Future Work

This thesis investigated the design process, introduced and implemented a genetic algorithm for a lighting design tool for architectural problems, and improved and tested a new daylighting glare index. The new daylighting design tool has been created and developed to address the major limitations present in today's lighting design process and computer-aided design tools. This chapter states the findings and reflections on this thesis rather than making certain conclusions. It presents the information is such a way that conclusions can be written. Then the future work is addressed.

10.1 The findings and reflections

The increasing complexity of information, processes, and technology makes expectation in design solutions more crucial than ever which does not mean that traditional methods of design are inappropriate. Such a process enables a designer to adapt his or her learning. From experience using numerous computer-aided design tools, the speed of processing or evolving tends to facilitate the user's ability to learn the process that the user has just undergone. Faster evolving process makes it easier for the user to reformulate the design problem. Thus, in order to learn from the tool, simple configurations would work best because it is easier to edit. Moreover, this thesis has incorporated a history database that makes the program about 60% faster. Besides, a new initialization function has been derived such that the designer could guess and input better genome that improves another 50% to 60% in calculation time.

Of all the observations and procedures that were done, the system procedure best illustrated how such an approach might be used in a learning situation. A designer using this program does not have to manually change a file and run it for each specific increment and configuration, considerably reducing the amount of time it takes to perform each analysis. A properly applied optimization procedure providing the designer with appropriate levels of solution and analysis will allow the designer to learn during the evolving process.

Once the design geometry has been described and the desired performance, variables, increments of step, and constraints have been specified, the user can investigate the changes in daylighting design solutions and their performance by comparing the evolved images of the outputs. The user does not have to specify the increments of the change during the evolving process since the system automatically generates the change based on the performance of the initial variables. The data are then passed to the analysis module.

After the solutions and the daylighting performance have been calculated, the user can view the results and compare many different images. The designer has the option of viewing results when he or she specified before running the system. Choices of the output can be customized to present score, illuminance level, contour lines, and values of each converged gene.

Finally, by utilizing the visual-information technique of multiple images of solutions, the designer is better able to perceive and compare the trends and relationships that emerge from the process. Small and multiple images depict comparisons, which are the essence of statistical thinking (Tufte 1997). Design performance score has been normalized and presented along with a visual image of actual illuminance levels. Thus, the value of these techniques as learning devices increases as the number of design variables increases. It enables the designer to expose many of the relationships affecting daylighting performance through the use of visualization.

10.2 Future Work

There are several concerns that need to be addressed. Most important is the development of the tool that takes account of the preferred interaction of majority of users. The system should also have built-in statistical abilities that store and know about the relationships between design and performance variables as well as the relationships about design context. This will be useful and helps it accumulate intelligence when more people use the tool. The results and images could be stored as a lighting scenario bank. When the designer works on the next similar project, a series of stored document and files can be retrieved. The next step could be more sophisticated. The process should be able to suggest design opportunities for an inexperience designer. It might suggest issues that the designer might have missed. For a more advanced level, when the tool has been used by the designer, it can be programmed to learn the designer's style. The tool can then be personalized so that the designer has his or her own style or representations. It is the same effect as a handwriting or voice recognition tool.

Lastly, in order to bridge a gap within the lighting-design community, knowledge generated from such activities in the design process should be able to reach them in a broad-based way such as through the Internet. This allows designers to link and exchange their experience of light to that of others in the process, for instance, owners, end users, and manufacturers. It is the hope that it will result in the design community in a virtual space that provides cost-effective and efficient design process and yields better design quality.

10.3 Conclusions

This dissertation documents my experience investigating design process, inverse method, and daylighting design issues. I feel strongly that the inverse method can be a valuable vehicle for such a task. Unlike researchers of the first generation, I believe that the inverse method and its application, especially this work, are useful, not for what they can evolve to a particular design solution, but for what they can bring to the designer. The inverse method applied within this framework developed by me helps assist the designer in clarifying and refining design issues. It supports the designer's confidence in his or her tuition. This system provides diversity of solutions to the designer which he or she might have missed. Properly applied optimization techniques can inform useful information to solve such a design problem.

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Appendix A: Log of Observations at IBM

The primary goal of this report is to provide information on a workplace design that promotes work efficiency through the interior environment and work processes. A direct observational technique has been used as a data collection method to gain knowledge about the way people behave in everyday office settings. Additionally, I conducted informal interviews with staff members. This research on environmental behavior can contribute to the information–gathering and decision-making processes that are part of the design process.

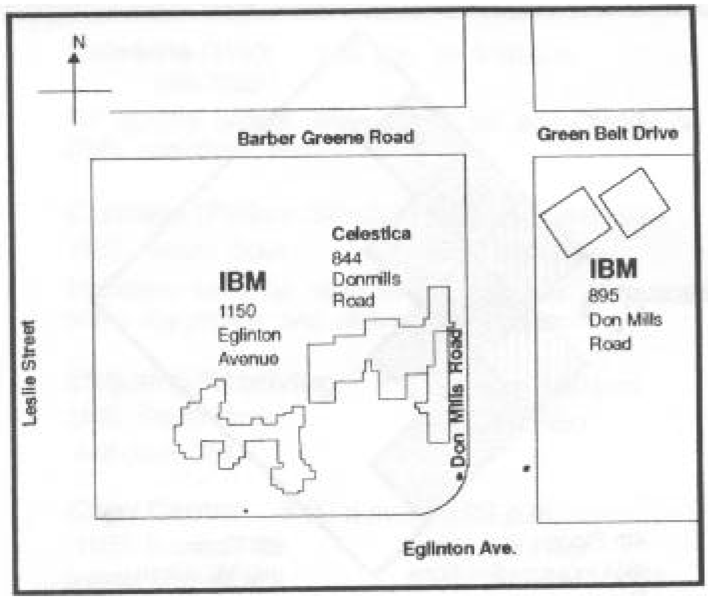
A.1 Logs: Observations

Date: January 5–14, 2000

The data presented here were collected during a two-week period of research at the IBM Toronto Laboratory, in Toronto, Canada. I observed, analyzed, and interviewed staff members within their pilot workplace and at the main laboratory where I worked. I collected data and information on a daily basis, according to my personal point of view and experience.

Location:

IBM Toronto Laboratory. The main building of this facility is located at 1150 Eglinton Avenue, at the intersection of Eglinton Avenue and Don Mills Road. It is accessible by car and bus. There are three levels in the building that are designated to serve 1500 employees in the software development section. Another lab site is located at 895 Don Mills Road, which is a fifteen-minute walk from the main building. IBM leases several floors in this office building. The pilot workplace is located on the fifth floor and serves about fifty employees.



IBM Toronto Laboratory and pilot workplace locations

(Source: IBM brochure for employees and visitors)

Date: Wednesday, January 5, 2000

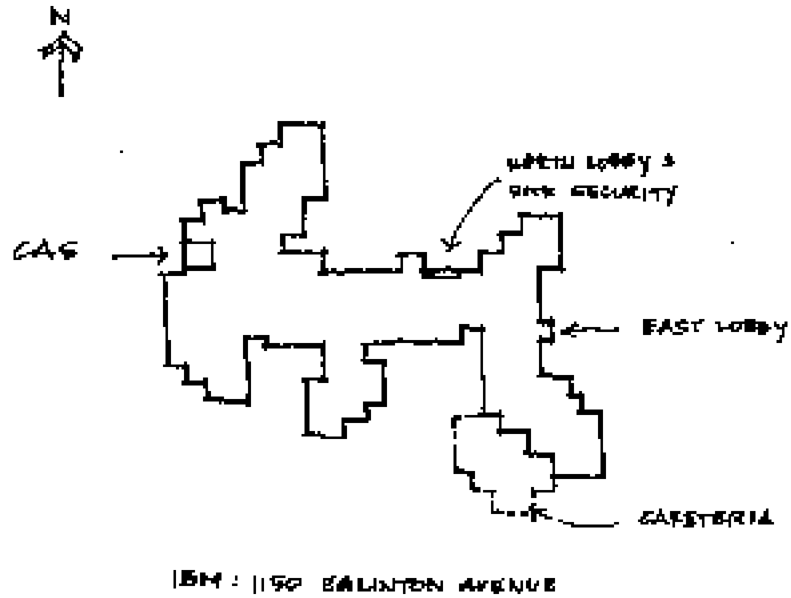
Arriving at IBM as a new staff member

What is happening?

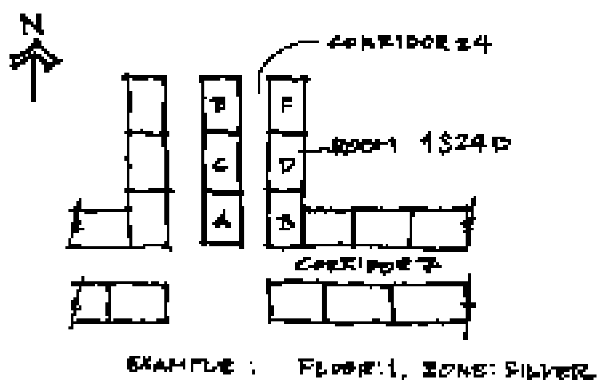
Today I arrived for the first time at IBM. As a visitor, I entered via the North Lobby, where a security desk is located. All visitors contact a security person or receptionist at the front desk, and get visitor badges while waiting to be greeted by IBM staff in the lobby area. In front of the entrance door I noticed a sign that read, "Do not tailgate." At nine o'clock, Chantal Buttery, a CAS (Center for Advanced Studies) coordinator at IBM, came to greet me and took me into the CAS office area, where I was introduced to George Bragg, who is also an intern student at IBM. His responsibilities include maintaining computer hardware and software systems, and ensuring that everyone at CAS is able to operate all computer and network facilities without any problems.

George gave me a tour of the building, explaining that it is divided into several zones, which are indicated by colors—green, blue, silver, purple, and red. The color zoning is helpful since the building is so large and the space is divided into many small individual rooms and public meeting rooms. Way finding is difficult and the layout is confusing. George said that N-S corridors in each zone are designated by even numbers and E-W corridors by odd numbers. Rooms in each corridor are identified by letters from A to Z. Thus room number 2G32M correspondents to room M, on the second floor, within the zone green, in the corridor number 32, N-S orientation. Many "You Are Here" maps are posted along corridors. And at several intersections, many signs are posted to indicate corridor number.

At lunchtime, I almost got lost when trying to find a cafeteria (for employees only) that George showed us in the morning. Fortunately, I recalled Christmas decorations near the cafeteria, and this "seasonal" color lead me to the right place. Without this reminder and the "You Are Here" maps, I might have gotten lost. I had to use my IBM badge twice in order to gain access at various spots along my path to the cafeteria.



The sketch shows the complex shape and plan of the large building. Notice the scale of CAS, which hosts about twenty full-time employees. To get to my temporary office space in CAS from the North or East lobby, I had to walk past other departments, which should not be necessity.



The way in which IBM Toronto Laboratory rooms are numbered.

My Interpretation

My initial experience and interpretation of the building is that it resembles a labyrinth. It is considered to be a deep-plan building to maximize the ratio of gross building area to its site area. Its corridors in the building are double-loaded to maximize the ratio of net usable space to gross building space. The design of the building results in a maze of corridors with no characteristics leading to a feeling of isolation with no sense of belonging, orientation, time, and connections to the outside. This feeling tends to make workers to lose their interests to the goodness of its organization. Even an employee who has been working for IBM for almost twenty years, got lost in a corridor, because the corridors all look alike. The room numbering system may not be very helpful in terms of way finding, because when people walk around, they do not actually read the numbers.

Since intellectual property is a major concern at IBM, due to the nature of its business, security is the main reason that people are not allowed to tailgate. However, the cafeteria, which is for the employees in the building, should be easily accessible.

Reflection

There should be a way to redesign the building layout so that majority of employees can gain access to natural daylight. The office layout should also be rearranged to improve way finding and orientation. How can the office plan be redone such that it reflects workflow and daily work activities?

Date: Thursday, January 6, 2000

Getting around the pilot workplace-POHD

What is happening?

At nine o'clock, Eli Javier, project executive for the new workplace environment, came to see us at our new assigned office in the CAS area. He took us by car to the pilot workplace, which is located across the street. It is a fifteen-minute walk to this location. The pilot area is on the fifth floor of the building, and serves about eighty employees. I had a chance to ask Eli about IBM staff and organization in the pilot space, so that I now have an idea of who they are and what their positions are within the company. There are two types of employees—managers and software developers. The ratio of manager to software developer is 1 to 9.

The responsibilities of the managers, in general, include handling projects, software development processes, and personnel management. The software developers' jobs can be divided into three categories—actual programming, testing programs, and technical writing. All employees in the pilot workplace are working on the same product on the different platforms such as Windows98, and UNIX. One product or software is composed of many components. Each component is assigned to a team. The number of people on a team varies from five to twelve to twenty people, depending on the characteristics of the component. The team meets about once a week. However, there are often meetings and discussions among groups of two or three people.

Eli took me on a tour around the space. There are four design configurations, which are called POHD (Personal Office Hybrid Design), Bungalow, Cul de Sac, and Control. Within each configuration group, there is a central team area. Additionally, on this floor there are two informal spaces for coffee breaks or informal discussions. These spaces are called Oasis areas. One Oasis area is for employees who are in Control space. Another is for those who are in POHD, Bungalow, and Cul de Sac. Eli introduced me to Bill MacIver, a manager sitting in POHD. Bill said "… I am sitting here … listening to one of my people in a separate POHD but with a connecting wall] and I can hear him turning the pages of a document at his desk!" I sketched and analyzed POHD configurations as shown. As I was talking to Bill, two staff members were using the team area, discussing new software on a computer, Windows98 platform. The configuration of the team area in POHD is presented in my sketch. Bill introduced me to Nick, one of the team members.

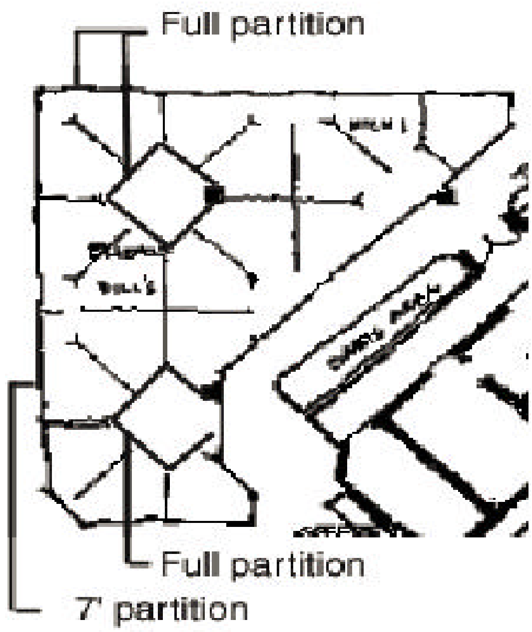
Nick is a software engineer, building components. He is very personable and is willing to give me information. He said that the team area is not large enough for his team. When six or seven people use the team area, they cannot actually accomplish very much, since there is a table with two computers in the middle of the area. White boards (doors) are all around the area. In fact, when they hold a team meeting, they normally use a formal meeting room, which is much larger. Nick's room in POHD is located across from the main entrance, as indicated in the attached plan. He has to walk through his friend's office space to access the team area. By the way, when I was talking to Nick, a staff member just entered her POHD. I could see her from the team area, since the door between her space and the team area was open. After a while, she closed that door for more privacy.

My Interpretation

This is my first observation of the pilot space. My impression is that the plan is confusing. This may be because I am unfamiliar with it. Even so, the pilot space is composed of too many different types of configuration. I probably should focus on the design and activities within each configuration. As a visitor, I think that the POHD configuration is too complicated. The space is triangular. The ceiling grids are also diagonal, a pattern necessitated by room shape. If I were here working, I would barely be able to concentrate on my job. I liked the concept of the flexibility of separation, or flow, using doors between individual spaces and team areas. A door is like a privacy sign, to be used when an individual needs to focus on his or her work. However, sound remains a problem that is unsolved by closed doors.

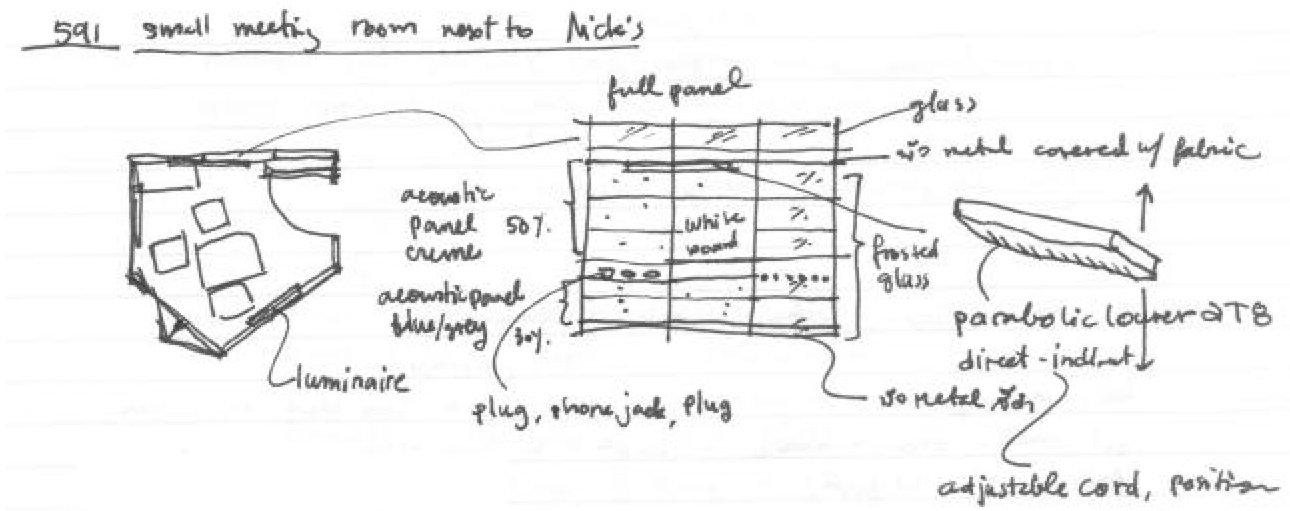
Reflection

Despite the full floor-to-ceiling partition, with a glass panel on the top portion that allows daylight to enter inner spaces, the area is still dark and sound is still a problem. Does the design of this kind of partition help solve the light and sound problem? A team area should be designed such that team members can access it without cutting through workspace. Nick should have been able to enter the team area without disturbing his friend. The team area configuration can be redesigned to better serve meeting purposes. Everyone should be able to see the whiteboard. Also, proper size, or flexible size of the team space, may be more practical than the present area's dimensions.

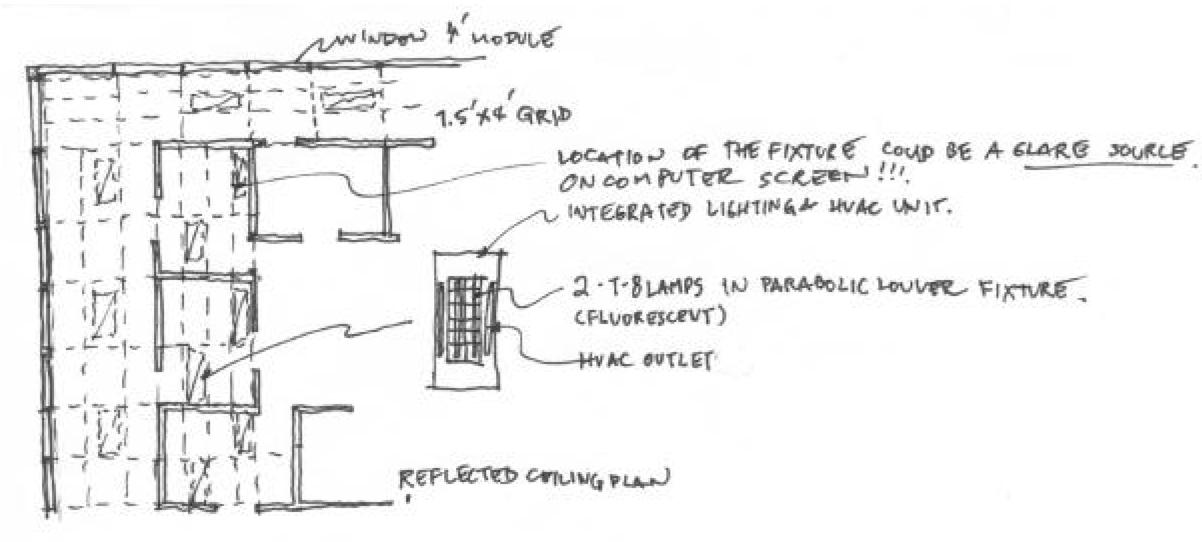


Two different types of POHDs. The difference is the height of the partition. Bill MacIver's office is located within the full partition design. The top portion of the partition, which is clear glass, transmits sound from other spaces to his workspace. Another problem is that the light transmittance of clear glass, about 75 to 85%, creates significant visual perception in the team area. I am able to see the difference in the brightness between the two designs. The one with the full partition is perceived as being darker and less pleasant than the other. Partitions of the team area are made of whiteboard, which is located at a good distance for seeing details of the material that is written on the board, since the team area is quiet small.

Perspective shows POHDs' team area looking toward individual spaces.
Source: IBM Intranet web site.



Small informal meeting room next to Nick's office. Parabolic louver, direct/indirect luminaires provide ambient light level and a nice atmosphere for informal meetings. Infrastructure such as white board, electrical outlets, phone and network receptacles, furniture style, and color schemes in the room enhance small and brief meeting activities. I used this space once for an informal meeting with Eli. I felt comfortable using this space to talk and exchange ideas with Eli regarding the pilot project.



Reflected ceiling plan in the pilot workplace. The design of the lighting fixture combines the lighting and HVAC outlet. However, some locations of luminaires can cause reflected glare on computer screens. My opinion is that the lighting fixture should be direct/indirect or indirect type in order to avoid discomfort glare and eye strain, which can reduce efficiency and employee work satisfaction.

Date: Friday, January 7, 2000

Getting around the pilot workplace-Bungalow, Control, and Oasis

What is happening?

This morning, Eli introduced me to Rajiv Datta, a technical writer. He is in Bungalow space. Most employees in this bungalow are technical writers; only one is a manager. Rajiv does not use the team area very often due to characteristic of his work. Most of the time he uses the computer to type documents. However, two to three people use the team area once in a while. And the team area is used for meetings about once a week. The lighting level and atmosphere in this area were pleasant, with plenty of daylight entering the space, but without direct sunlight. The partition is not a full partition. It is about 7 feet high, as shown in my sketch. It is more practical and simple than the POHD partition. I was visiting in Rajiv's space, I could hear distracting noise from slamming doors, printers, and the coffee area because his office is so close to the doors and public area.

Eli took us around the pilot area again, where we met a lady from the ninth floor, who works in a marketing department. She was on the fifth floor because she enjoys getting a free cup of good coffee from the machine near the Oasis area. Eli told me that the coffee is very popular among IBM aemployees in this building. No wonder this area is always crowded and noisy. Employees are happy to use this area, for coffee breaks, talking, and socializing. However, I noticed that office doors around the coffee area and Oasis are closed. Employees complain about the noise level from these areas.

Later, Eli introduced me to Murat Sandikcioglu, who is a manager. He works in a typical rectangular office space, with direct access to windows and a view. Please see my sketch for analysis. Windows were large, stretching from wall to wall, and from desk level to ceiling. Blinds were up all the way to ceiling. His largest desk, or main desk, faces the windows, but he sat at another smaller desk facing the wall. Here he worked on his IBM ThinkPad Notebook. The sky condition was overcast resulting in a very bright white sky that could be considered a source of glare.

My interpretation

The layout looks right to me, except that it is located close to the public area. Noise is a major problem.

The coffee machine seems to be a drive booster for employees.

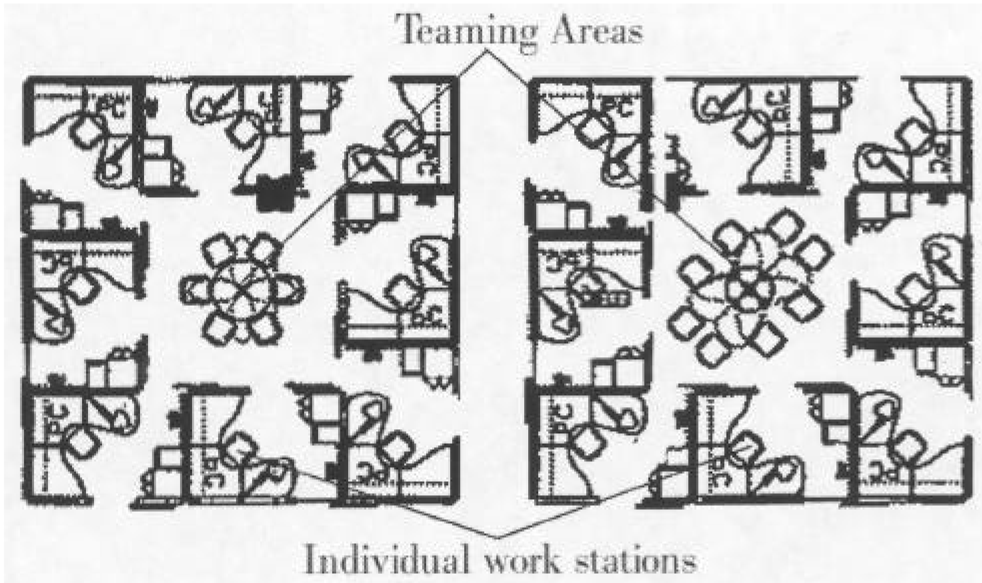
The advantage of Control space over other spaces is its view and natural light. But only office spaces along perimeter of the building can access natural light, while the majority of workers in Control office spaces, in the inner area, have no access to natural light. In the Bungalow, office space accesses plenty of light, since the corridor is next to windows and partitions are only 7 feet high.

Reflection

While the coffee machine makes its users happy, some people are disturbed by the noise and aroma. It may be better to tie the Oasis area and coffee machine area together, but separate them from office space in order to prevent distracting noise.

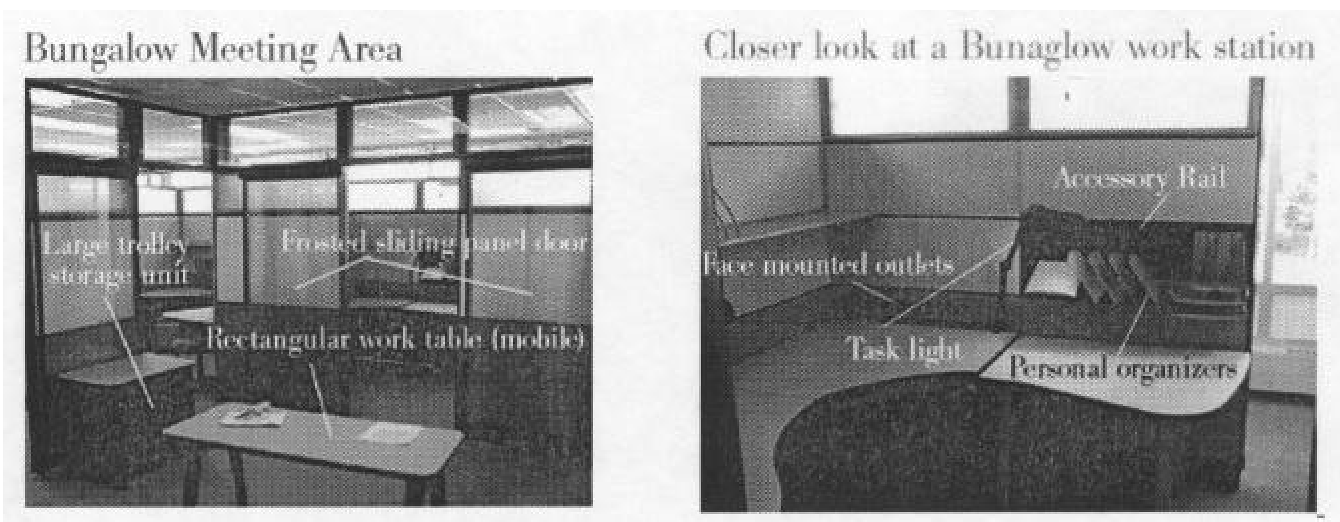
Doors are very important. There should be a noise absorption device at doors which is activated when doors are closed. Door material and detail should also be considered from an acoustical standpoint. The printer area should be designed in closed space to reduce nuisance noise from this source.

Glare from windows is also another important issue. Once blinds are adjusted, people do not seem to readjust them during the day. An automatic dimming system, or shading device, may be helpful for the existing building. I do not think it is a good practice or fair one to place individual workspaces next to windows. View and natural daylight should be accessed by the majority of employees, not a select few. All workers should benefit from daylighting conditions.



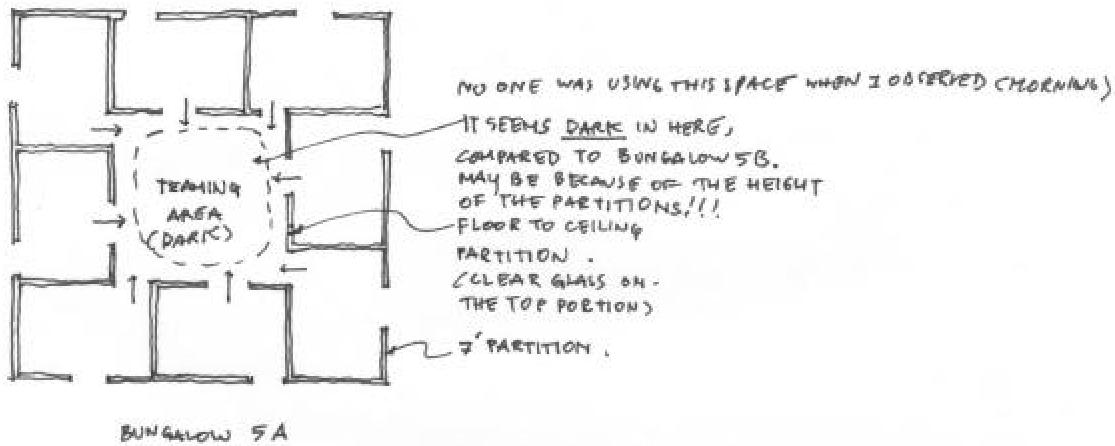
Bungalow design and furniture layout

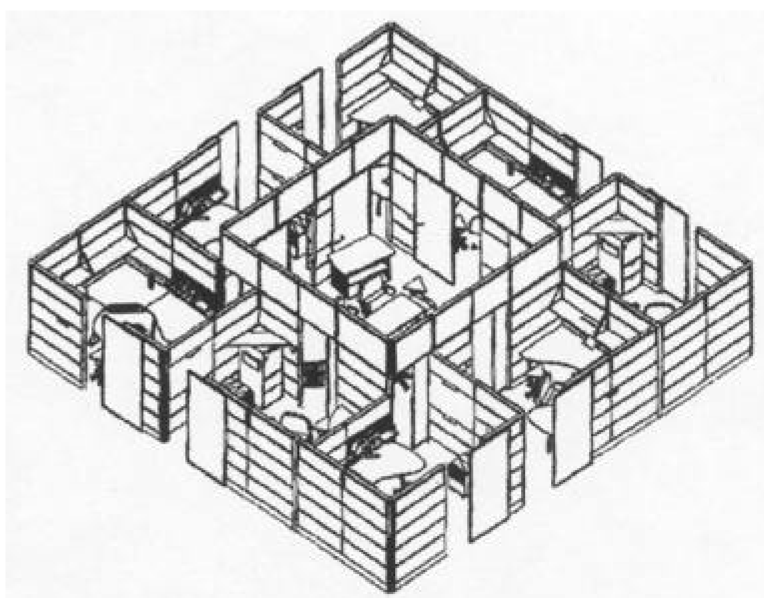
Source: IBM Internet web site



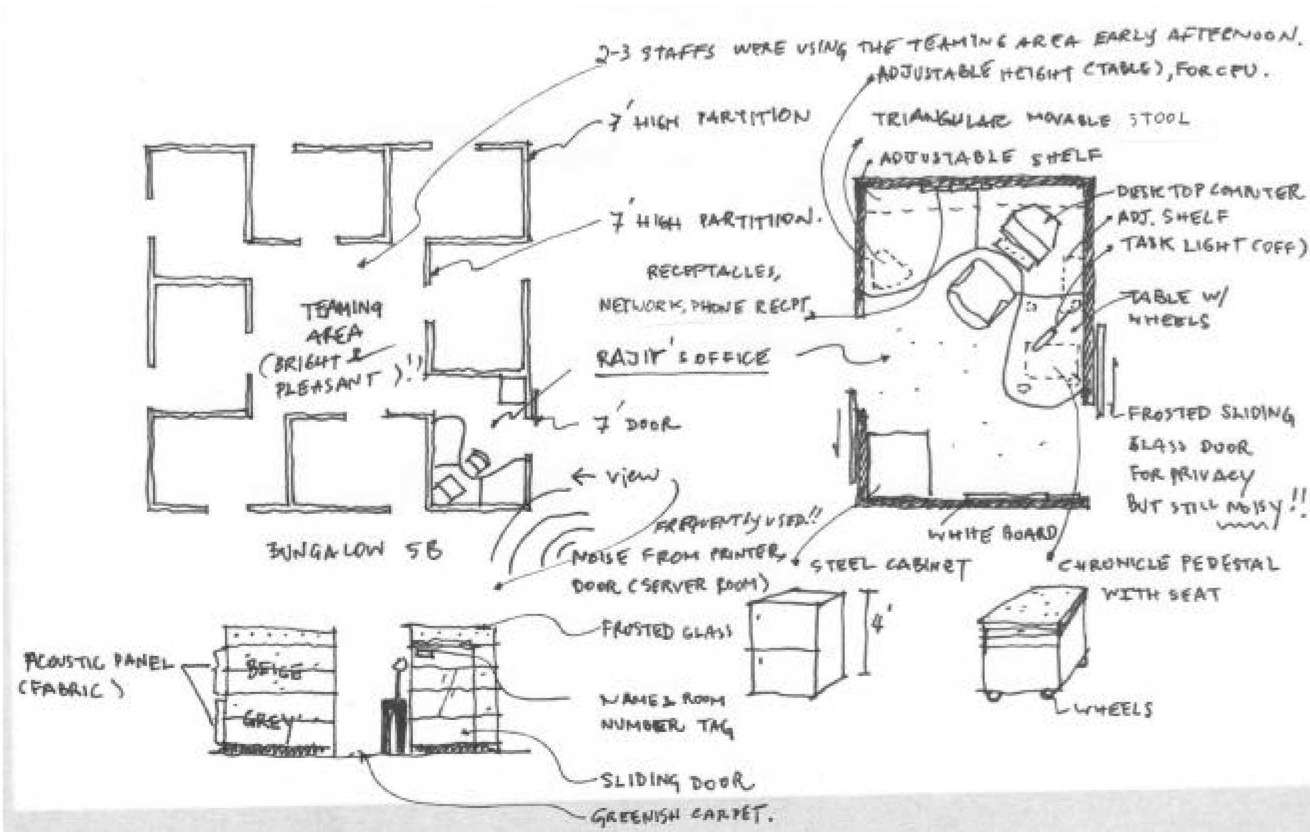
Pictures show Bungalow 5A team area and an individual workstation.

Source: IBM Internet web site

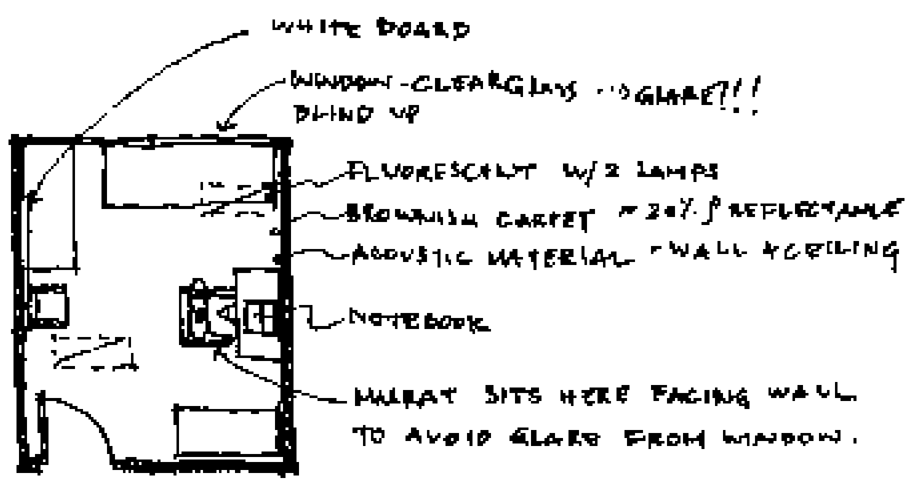




Bungalow 5A plan and isometric drawing



Rajiv Datta's individual space within Bungalow 5B



MURAT SANDIKCIOGLU'S OFFICE

Murat Sandikcioglu's office is located on the other floor. It is conventional style.

Date: Wednesday, January 12, 2000

Setting: an interview with Rajiv Datta

What is happening?

After my lunch, I waited for Rajiv at the Oasis area. I was the only one seated here. Whenever I have been at the workplace pilot, I have never seen anyone using this space. I heard some noise coming from the coffee bar. Curious, I walked there and met a software engineer who was warming his lunch in the microwave. He helped me get a free cup of hot chocolate from the coffee machine, an employee amenity that I, too, enjoy. The engineer's name is Rayman Lei. His office is in conventional space. He is very friendly and is interested in my research. He volunteered his opinion on the pilot space, saying that he did not like the new space that much. His reasons were: 1) the pilot space looks too fancy, 2) the space is too busy to allow concentrating on work, and 3) the doors are unattractive because they are like temporary doors.

After our short conversation, I went to see Rajiv at his Bungalow space. The detail of his office and team area is shown in my sketch. He offered me a seat on a triangular-shaped stool for guests. Later, he changed his mind, saying that we should go to another room so that our conversation would not bother other people. He took me to an interview room, where our talk began.

Rajiv is a forty-one-year-old technical writer. He is one of twelve members on a team writing Install Configuration for a software product. His task is to write the user manual and online help. About once a week, he and his team get together for a meeting in a team area. Here, they put all documents together, and test them using computers available in the team area. Rajiv added that once in a while, his team has meetings with another technical writing team in the other Bungalow space. The other team is writing the Getting Started section. Because of the nature of his task, Rajiv must deal with software developers, testers, product planners, and managers, either in person, or by phone, or e-mail. They are all in the same area.

Rajiv's major problem regarding individual space is storage space for documents. Storage spaces in his office space are not large enough, and they are awkward shapes. He said that the storage spaces are very inefficient for storing books, documents, files, and manuals. He did not like to have to adjust and assemble cabinet files when he wanted to access material. He preferred a ready-to-use cabinet. He is looking for more facilities, such as dividers and hanging folders. He never used the triangular-shaped stool because it is not very comfortable. However, it is compact and is suitable for guests who visit briefly. The size of his work place is adequate. But facilities to store and organize his documents are the most important thing for him.

The team area is a good size. However, accessibility is a problem for outsiders, since they have to cut through other people's workplace to reach the team area. Rajiv added that light and noise from the team space and environment are not actually problems for him, since he is an adaptable type of person. He liked the team area, since it gave access to natural daylight. One major problem that he raised was privacy, both visual and acoustic. This was especially true for his boss. When the boss needed to make a confidential phone call, he had to walk to the interview room, which absorbs noise. On the positive side, Rajiv commented that he liked the coffee bar, since it offers free good coffee. He uses it three or four times daily, but he never uses the Oasis area at all. He would not want to be seen in the Oasis area, because he thinks of it as a place where employees "goof-off."

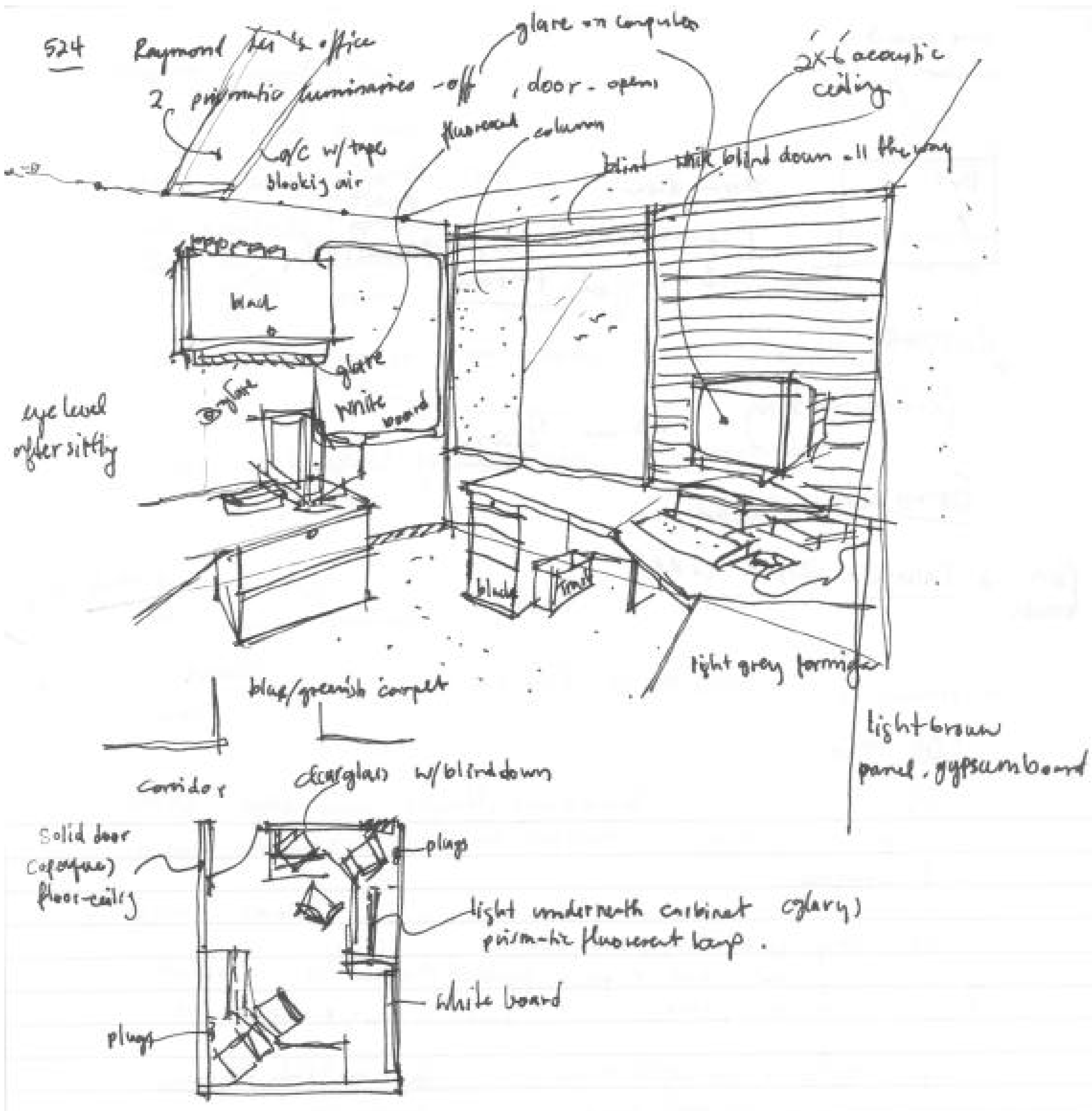
My Interpretation

The kitchen area is a common space where people can make new friends. It was the only place where I got to know people who were not introduced to me by Eli. I could see that people who used this space exhibited more eye contact than those at other places on this floor.

Different task characteristics require different design configurations. In Rajiv's case, he is a document writer dealing with lots of documents. Therefore, he needs good storage and accessories to organize his documents. A partition height of 7 feet is a trade-off between lighting and acoustics. While it provides more natural light, it does not dampen noise. The pleasant coffee and service facility is a plus for employees and for visitors like me.

Reflection

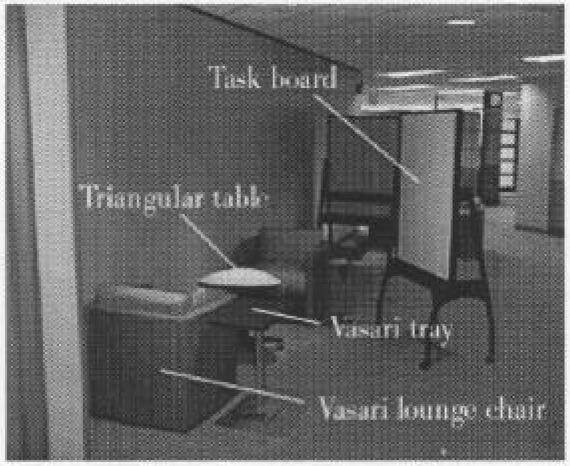
The privacy issue should be considered as an integral part of the design configurations, in terms of both planning and material selection. Material selection for Rajiv's door may be optimized in order to gain the most natural light, while also keeping the noise level low. However, visual privacy should be taken into account as well. The Oasis area may be utilized by combining this space with the coffee bar area. Given the fact that sitting at the Oasis area may be considered a sign of wasting time or goofing off, it is likely that this area may be used very little or not at all. However, coffee break time should be considered a good thing, a necessary break that helps improve work efficiency.



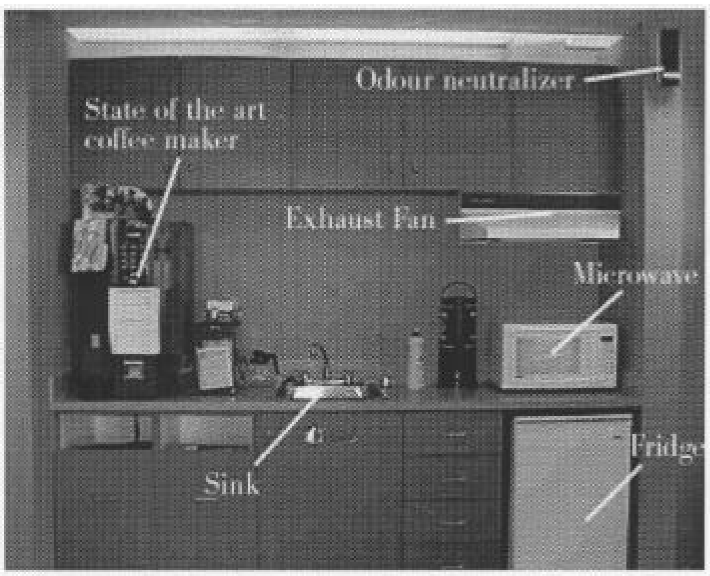
Raymond Lie's office located in Control space

Typical Control office space

Source: IBM Intranet web site



Oasis areas for employees to relax and have a casual meeting.



Kitchenettes featuring basic amenities.

Oasis and Kitchen areas

Source: IBM Intranet website

Date: Thursday, January 13, 2000

Using Skills Center

What is happening?

Bill O'Farrel, research assistant at CAS, is helping me study how to make my program available on the Internet using VisualAge Java (VAJ) and WebSphere. I realized that I should at least know some background on VAJ and Java. Today, I stopped by the Skills Center hoping that I would obtain help to better understand this new piece of technology. When I arrived at the Skills Center on the third floor, I had a problem with my access card. It did not work properly, since I need special permission to use it. A librarian opened the door for me. We went to check my permission. Everything looked fine, so next time I should not have this problem. When I went in, there were several people using the library.

The librarian explained that this library is also available on IBM's Intranet (local people only). The contents of the library include computer journals, magazines, manuals, software, programming books, self-study courses, and computer workstations. Its size is small, because most materials are in digital format. However, some content, such as online electronic journals, technical reports, and self-study materials, cannot be browsed without accessing them from the library. The library is open twenty-four hours, by badge access. Employees can check out books by themselves, using two computers provided at the front desk. I realized that this library is a heaven for people who want to become experts in programming and computer sciences. Later, the librarian showed me how to use a workstation for self-study.

All materials were already loaded on the workstations, which are located in booths. However, CDs and binders are also available to take home. Self-study materials were prepared by IBM for IBM. The company has made them easy to understand and interesting to use as learning tools. There were also video scripts, together with explanations and examples on the web. I very much enjoyed using the self-study workstation. The self-study courses available in binders also offer the advantage of rapid acquisition of depth of knowledge. I am certain that I will be returning to the library. Its only drawback seems to be the furniture and lighting condition. I would like to see natural light entering the space.

As I was writing this log, George Bragg entered my office. He said that he has just finished teaching his course. He was an instructor for the Linux course at IBM, which is free for all employees. George said that this topic is very popular right now, because it could represent the future of the software industry. IBM also offers employees several courses and lecture series that are related to the software development process. These courses are taught by CAS personnel.

My Interpretation

It seems to me that one reason why IBM is producing top products, is the strength of their support facilities, which play an important role in the product development process.

Reflection

Would the learning experience be improved by visual cues in the building interior, especially by the introduction of natural daylight into the room? I would like to see IBM materials available on the Internet, so that people would learn more about them. I believe this exposure would accelerate progress in the research and development community.

Date: Friday, January 14, 2000

Setting an informal discussion with Eli Javier

What is happening?

At ten o'clock, Eli came to see me at my office. I did my homework, researching the corporate organization and the Toronto Laboratory. He was kind in explaining to me about the system at IBM and its relationship to the Toronto Laboratory. I have attached the organization chart, as shown below. People who will be using the new workplace are from the Software Solutions Division (Data Management and Application Enabling and Integration) and Internet Division (E-Commerce). Employees range from high-level directors and function managers to product managers, managers, and staff members. Products created within Data Management in the Toronto Laboratory include database management tools, such as DB2. Products from Application Enabling and Integration are VisualAge e-business, VisualAge for Java, C++, and RPG, Fortran, HPF, and Visual Banker. The Internet Division produces World Purchasing Pro, Net.Commerce, CSS (Customer Support Service), etc. Those who work in the workplace pilot are the Electronic Commerce development team. The rest of the staff work in the building where my office is located, (1150 Eglinton Avenue East) and at 330 University Avenue.

Eli added that nature of work at the lab is truly dynamic. He has never worked on the same job for more than two years, because there are always new products and advances. These days, it takes twelve to eighteen months to complete a software product. The process is getting shorter and shorter every day. Once a product has been completed, a new project is immediately assigned. Managers and staff may be relocated, depending on their skills, what products they would like to work on, budget, schedule, and availability of staff. Most of the time, the work assignment decision has been made by managers. Therefore, when a project is finished, team members may or may not remain on a team.

My Interpretation

I liked the idea of a dynamic work environment, because employees have opportunities to gain new knowledge, and to meet and work with new people. However, special care is necessary to custom-tailor design and networking systems to fit into software development activities.

Reflection

To design the workplace and its furniture for dynamic activities is not easy because each task differs in detail due to its specific characteristics. Providing for flexibility and adaptability would key factors in the design process. A hierarchy of privacy levels should also be considered in the design process.

Appendix B: Log of Observations with a Lighting Designer

The purpose of Appendix B is to describe the processes and ideas that were part of finding a solution to the lighting-design problem I studied while working with a lighting designer. My work with this company led to my design of software for daylighting design applications, specifically geared for the architectural lighting-design process. Finally, I discuss the knowledge and understanding that emerged through this process, as well as the design outcome of the process itself.

B.1 Artificial lighting design and process

The very first exercises were to use Lumen Micro version 7.0, importing photometry data, and analyzing results from different types of lighting distributions from such luminaires. From these exercises, I could learn about and get a sense of the relationship between light sources and spaces. We then began with real projects: artificial lighting design in interior spaces, after objectives and program needs had been defined. The designer first determined design concepts and lighting conditions by examining both plan and section. At the plan, he designed the circulation concept while seeking more opportunities or options for arrangement of other systems at the section. During this process, we looked at planned materials to accommodate constraints such as the reflectance of room surfaces. Finally, the designer created alternative schemes for comparison and evaluation.

Once the design concepts had been established, a lighting-concept diagram in three dimensions and in sections and plans was set up. During this stage, desired light distribution, lit surfaces, as well as locations, layout, and types of light sources were generated, based on all building systems. This process was then followed by design and development, which included selection of several alternatives of lighting fixtures, architectural details, energy inputs, and cost approximations. We used Lumen Micro to analyze illuminance levels and luminance levels, with the hope that the design could generate effects that were close to the designer's original design concepts. The space we modeled in Lumen Micro was simplified, so that we could easily achieve estimated results, and easily change and evaluate other design options. If such results provided different conditions than the goals, we changed to new lamp types, luminaires, or layout, then analyzed the new results. Our basic process was one of typical trial and error.

The designer had several concerns regarding the use of Lumen Micro. First, it was difficult to enter data into simulation programs. Second, it caused a computer crash before we had an opportunity to save a file. Finally, Lumen Micro requires an IBM-compatible computer, while most designers have been using Apple. Many lighting designers I know invested in PCs for the sole purpose of using Lumen Micro. A user-friendly, web-based design tool would work perfectly for architects and lighting designers at this point in the design process. However, based on my observations, I believe the designer possess thorough knowledge derived from his extensive experience in lighting design, where he does not actually need such computer-aided design software. Most of the time, he could select the right luminaires immediately before running simulations via Lumen Micro. The designer was able to do this by determining their candela distributions and their relationship to spaces, such as distance from ceiling, wall, task, and other fixtures.

The role of Lumen Micro was as a confirmation tool only for his design. It was used to print out renderings, illuminance, and luminance level for presentation to clients. This led me to think that a designer, after long experience in the use of design tools or in the design process, would actually no longer need to use this type of design tool after initial mastery. Thus a good design tool should be a good learning tool as well. Using a design tool should be a learning process whereby the designer knows the input parameters and output performance, and can compare them during the design process.

B.2 Daylighting design and process

The same trial and error process occurred during the course of the next project on which we collaborated. This project was a daylighting design for a library, an assignment the designer took from an architectural firm. The main purpose was to control the appropriate amount of daylight and its distribution into the building. After biological needs and activity needs had been established, this time, instead of using Lumen Micro (with its limitation in generating a sloped surface), we built a scale model, with three different skylight control strategies to evaluate and visualize building performance. The model had three openings, which allowed us to look inside it from different views and angles. The openings could be closed when our measurements were in the process of being made. Upon finishing construction of the model, our big problem was the need to wait until the sky was perfectly clear or totally overcast in order to measure amount of light under prevailing conditions with each of the design options. For each test, the different sensor locations need to be recorded under identical sky conditions. Therefore, the problem with this real sky testing method is the fluctuation in sky conditions such as partly cloudy sky and/or windy conditions. Measuring the model under windy condition could be a disaster because the wind could destroy the model or blow off movable parts of the model such as its roof.

The designer invented his own measuring equipment so that a model could be attached to it. The equipment was capable of being rotated to simulate different times of day throughout the whole year. The model was tilted with the aid of a sundial. See Figure B.1 for detail of the equipment.

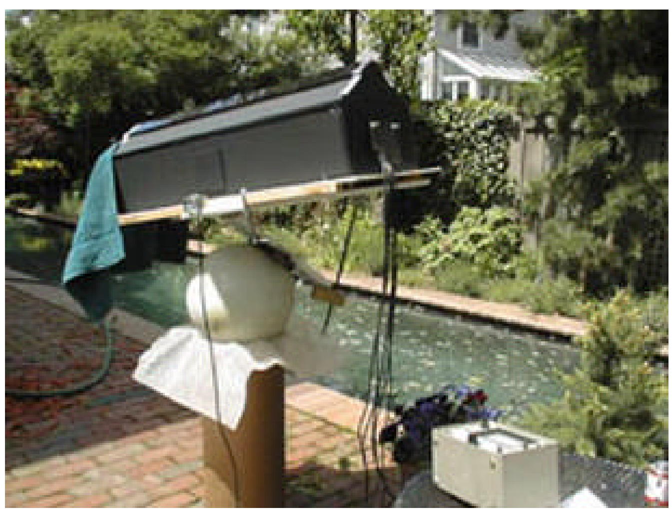


FIGURE B.1 TILTING MODEL AND MULTIPOSITION METER WITH SENSORS

For this particular library project, we measured and examined each design option under three seasonal conditions: equinox, summer, and winter. For equinox and summer, we investigated the models from 9.00 a.m. to 6.00 p.m. and for winter, we evaluated them from 9.00 a.m. to 3.00 p.m., in a three-hour intervals throughout each time range. We placed five small illuminance meters with sensor inside the model and one illuminance meter on its exterior, which enabled us to measure illuminance levels from the sky as a reference, to be used to calculate approximate values in the real space. The meter locations in the model were: one in the center and four at the corners, about two-thirds of the length and width of the room. By employing this method, qualitative and quantitative measurements of model spaces could be recorded, photographed, verified, and judged by the designer. Nevertheless, there were limitations namely, a limited number of design alternatives due to time and cost constraints.

Once all readings and photographs had been taken, the next step in the process was to organize and analyze the designs. In order to perceive and understand the difference of daylighting conditions among each option, the designer organized outputs into three types of data sets. The first set was visual images for each design scheme throughout the day and the three seasons selected (Figure B.2a to Figure B.4c). The second set was graphical images derived from an Excel spreadsheet, which compared performance of all schemes throughout the day for each season and sky condition (Figure B.5). The third set was of comparisons among all schemes under clear sky conditions looking at a front view and a side view of the roof (Figure B.6a and B.6b). Figure B.2a to Figure B.6b present the organization and results from the model testing. The designer looked at the first and second set back and forth in order to process the data. Based on these results, the designer made a decision to try more schemes, which were similar to the first three schemes, except in the area of glazing and its transmittance. Another problem here was that we needed to change skylight materials, set up all equipment, and wait for perfect skies in order to measure the building performance. To me, this appeared to be an impractical task, and its necessity made me appreciate computer design tools. They could be useful in predicting variations of properties of daylight in such a space throughout the year, under any sky conditions and in any locations. I also learned that graphical output is an important element in the process, enabling one to gain a clear idea and picture of what is taking place.

Although all schemes allowed a small amount of direct sunlight to penetrate into the space generating some high contrast, we would not perceive this phenomenon as glare. I realized that glare cannot be measured by ratio or by formula, but is perceptible only in its context, and can be judged by human perception and experience. It was also the designer's intent not to cover up all pf the existing skylight with low transmittance material, since he knows the importance of the biological need to see sky from within the space. These designs were based on task and objective prioritization. The low transmittance roof could save more energy for cooling load but it gave the worst visual perception and resulted in a dull feeling, since there was no connection between human and outside worlds. Finally, he hired a consulting firm to calculate heat gain through the skylight for all options that would help in selecting the final design.

In summary, my experience in working with this company gave me more insights in the area of what to do and not to do in the design process, rather than showing concrete findings. Knowing what not to do taught me that my thinking needed to be very broad in scope. I eliminated the new daylight glare formula from my original objective function. Indeed, I realized my original ideas needed to be re-evaluated. It would be possible to try to optimize building lighting design based on one or more criteria. However, I also saw that a software system would be valuable in the design process as a tool to generate design options that cut down on energy consumption, provide appropriate sound condition, and indoor air quality, while maximizing the use of daylighting, and achieving desired lighting conditions for specific activities and times of day throughout the year. The software must have the capacity to explore the trade-off between different building configurations and must be able to track cost associated with each design scheme as it is being simulated. Moreover, sensitivity studies could be undertaken to determine which parameters are most critical and should receive the most attention in the design process. On the computer input side, it could be anything that is considered user-friendly, depending on the work style of each user. At a minimum, a common "universal" user interface should be incorporated that could accept and process all necessary information.

FIGURE B.2A BASE CASE: EQUINOX

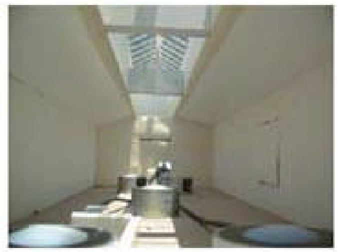
FIGURE B.2B BASE CASE: WINTER

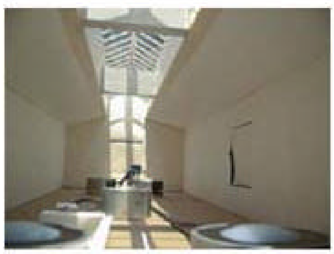
Case: Base Sky: Clear Season: Summer Time: 9.00am

Case: Base Sky: Clear Season: Summer Time: 10.00am

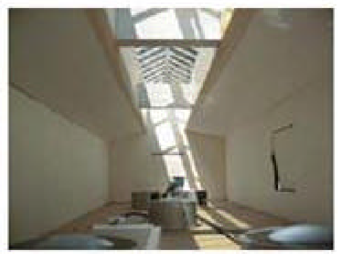
Case: Base Sky: Clear Season: Summer Time: 11.00am

Case: Base Sky: Clear Season: Summer Time: 12.00pm





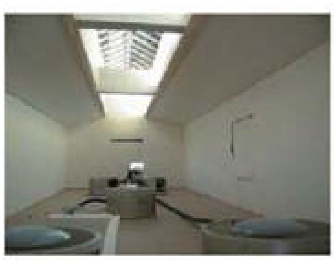
Case: Base Sky: Clear Season: Summer Time: 1.00pm



Case: Base Sky: Clear Season: Summer Time: 2.00pm

Case: Base Sky: Clear Season: Summer Time: 3.00pm

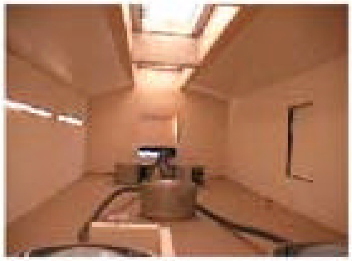
Case: Base Sky: Clear Season: Summer Time: 4.00pm



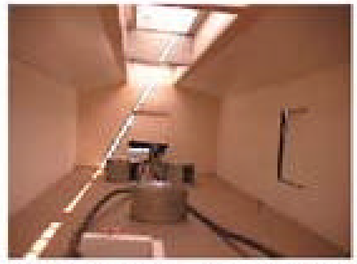
Case: Base Sky: Clear Season: Summer Time: 5.00pm

Case: Base Sky: Clear Season: Summer Time: 6.00pm

FIGURE B.2C BASE CASE: SUMMER

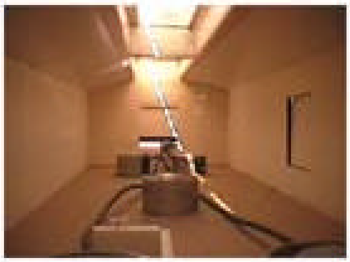


Case: Scheme 1 Sky: Clear Season: Equinox Time: 9.00am



Case: Scheme 1 Sky: Clear Season: Equinox Time: 12.00pm

Case: Scheme 1 Sky: Clear Season: Equinox Time: 3.00pm



Case: Scheme 1 Sky: Clear Season: Equinox Time: 6.00pm

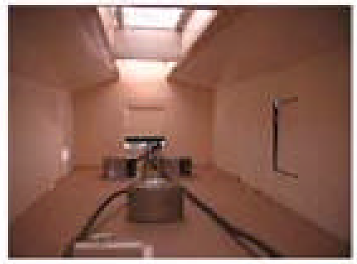
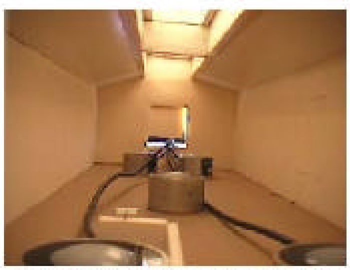
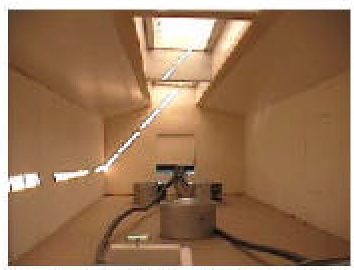


FIGURE B.3A SCHEME 1: EQUINOX



Case: Scheme 1 Sky: Clear Season: Winter Time: 9.00am



Case: Scheme 1 Sky: Clear Season: Winter Time: 12.00pm

Case: Scheme 1 Sky: Clear Season: Winter Time: 3.00pm

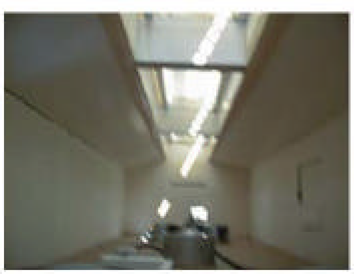


FIGURE B.3B SCHEME 1: WINTER

FIGURE B.3C SCHEME 1: SUMMER

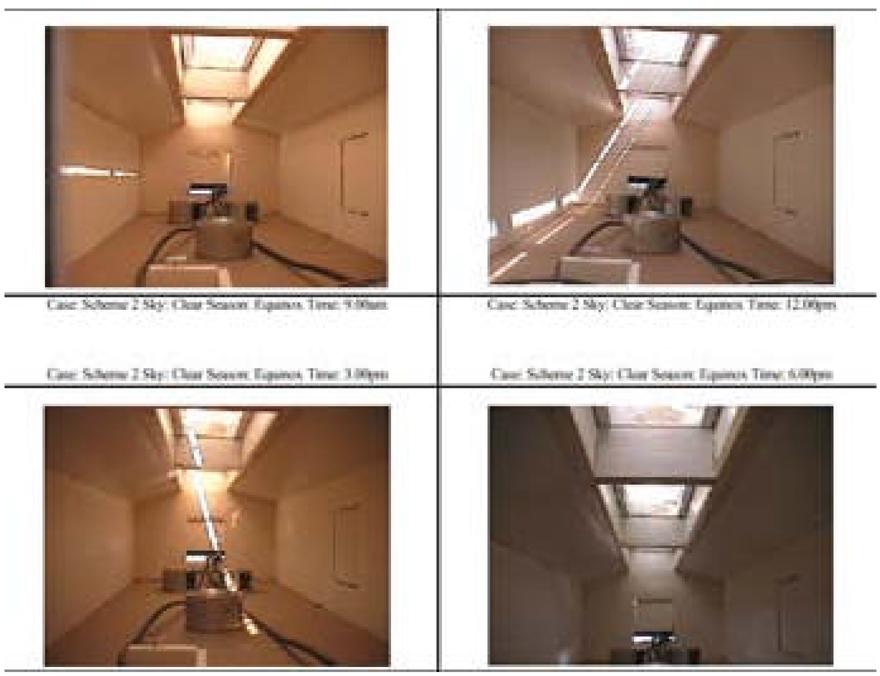


FIGURE B4A SCHEME 2: EQUINOX:

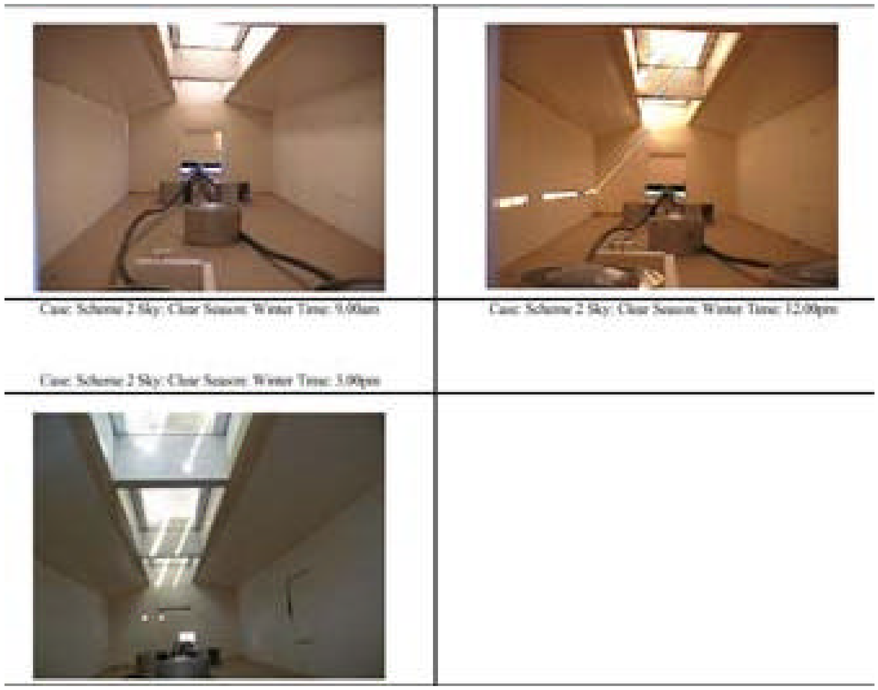


FIGURE B.4B SCHEME 2: WINTER

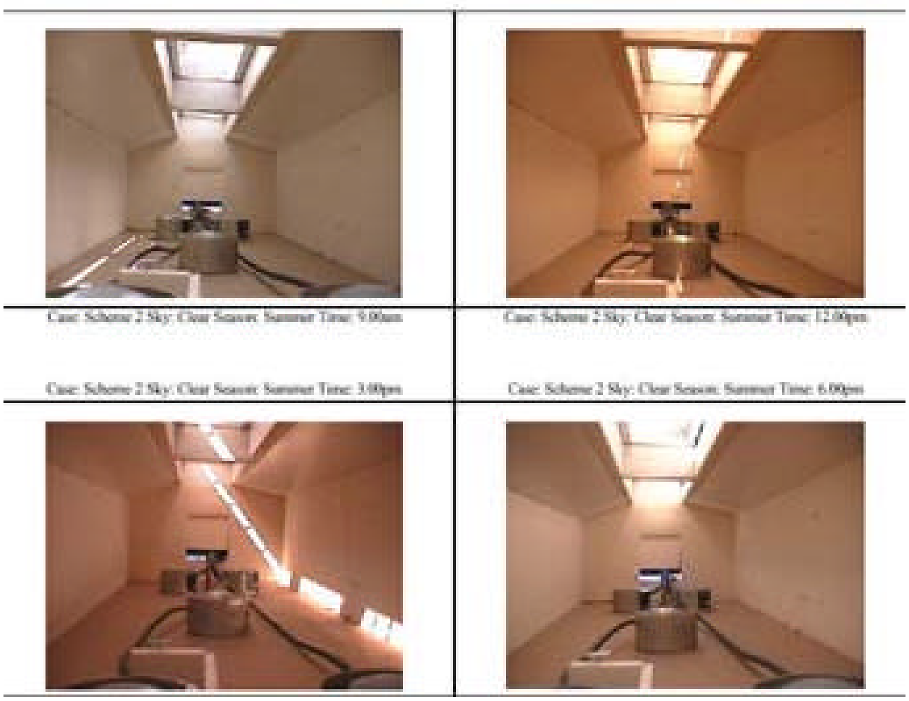
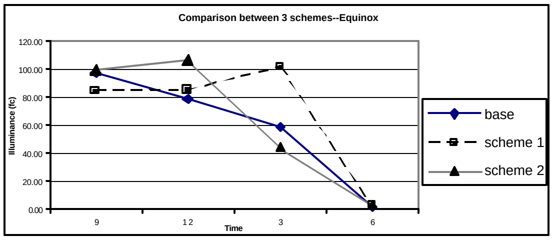
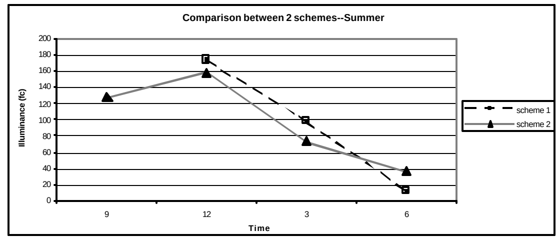


FIGURE B.4C SCHEME 2: SUMMER:

	Equinox	Equinox	Equinox	Equinox
	9	12	3	6
base	97.26	78.61	59.30	1.85
scheme 1	85.09	85.58	102.32	3.43
scheme 2	99.59	106.76	44.39	3.26

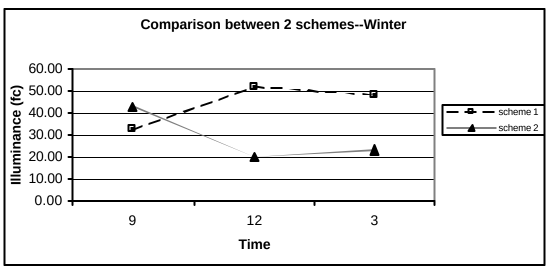
	Summer	Summer	Summer	Summer
	9	12	3	6
base				
scheme 1		173.40	98.07	13.03
scheme 2	126.87	157.37	73.24	36.46

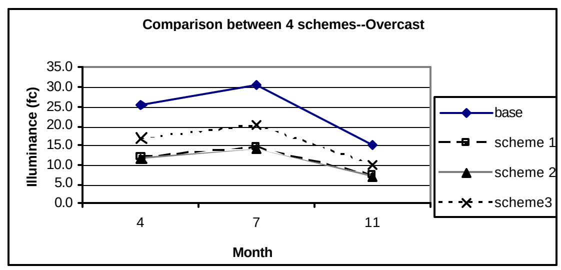




	Winter	Winter	Winter
	9	12	3
base			
scheme 1	32.45	51.76	47.88
scheme 2	42.67	19.99	23.17

	Overcast	Overcast	Overcast
	4	7	11
base	25.2	30.6	15.2
scheme 1	12.12	14.67	7.27
scheme 2	11.6	14.1	7.0
scheme3	16.8	20.4	10.1





Note: The averages exclude measurements in direct sun.
Note: Horizontal illuminance from sun and sky are obtained from the IESNA Lighting Handbook, 1999 edition.

FIGURE B.5 GRAPHICAL DATA

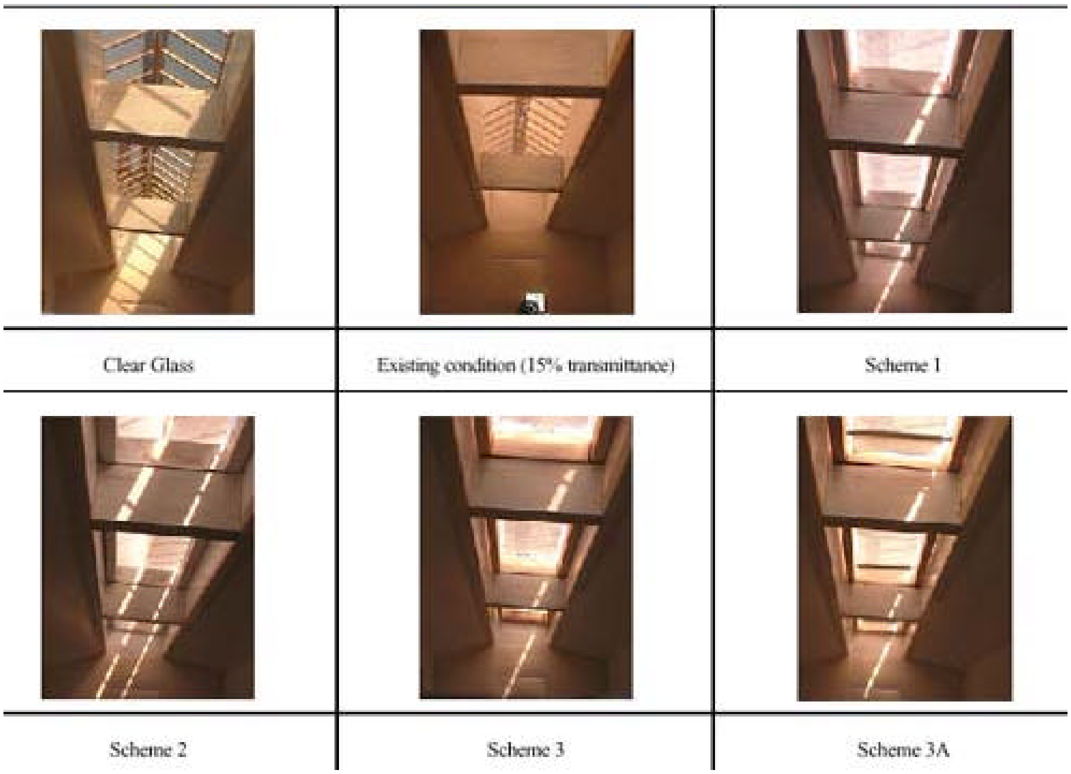


FIGURE B.6A COMPARISON OF ALL SCHEMES: FRONT VIEW

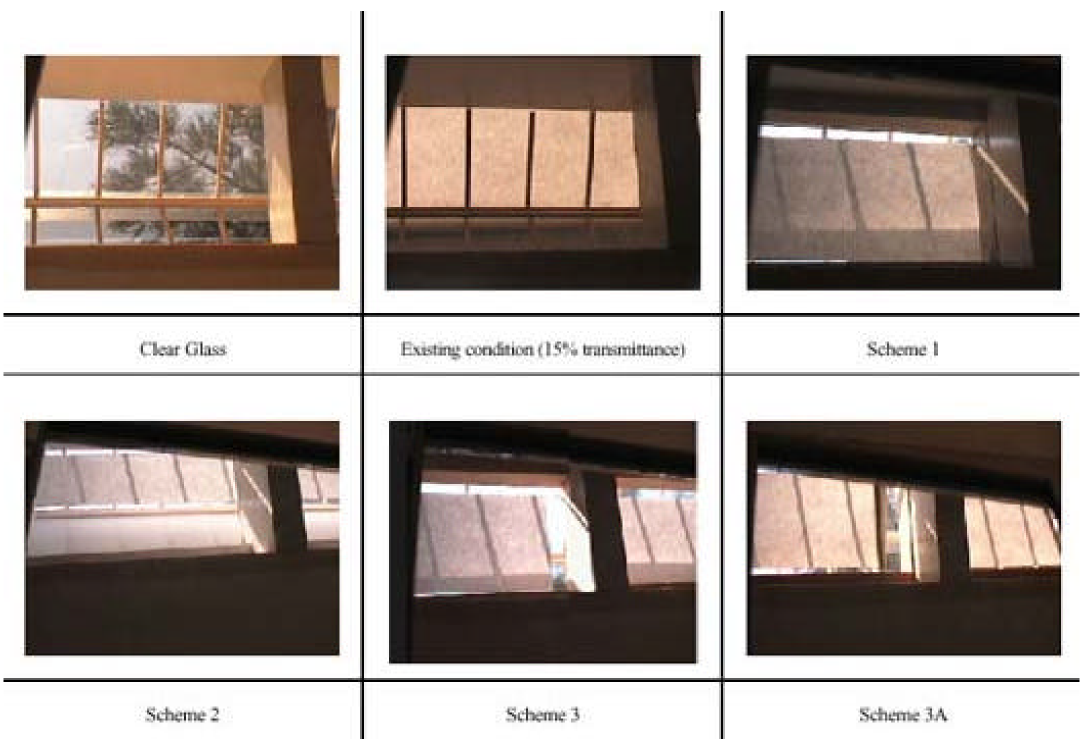


FIGURE B6B COMPARISON OF ALL SCHEMES: SIDE VIEW

Appendix C: Questionnaire and Interview

In order to achieve meaningful information, it is necessary to consider the physical attributes of the places being evaluated, the users who participated in the setting, and the environmental context or the characteristics that impinge upon the setting (Sanoff, 1978). The following testing procedures and questionnaires have been developed from Friedman's questionnaire to assess the technical aspects of visual performance. The questionnaire was presented to 29 IBM staff. Responses to the questions provide more accurate definitions of user needs. In particular, the responses define the subjective comfort level as well as preferred or expected lighting conditions in workplace. The statistical results are presented in Appendix D.

C.1 Objectives

The study will take place in workplace at the IBM. There are three parts: free interview, daylighting experiment and questionnaire. The interview will take about 7 minutes, which allows subject's eyes to adapt to the experiment room. The objective of an interview survey is to gather series of experienced facts in practice and representations, which establish the transition between personal life and collective patterns common to a population. After information is collected and eyes are adapted to the environment, then the experiment shall begin. The second part will take about 5 minutes. The purpose of the experiment is to validate a new daylight glare evaluation method and an objective function used in a design tool. Then questionnaire regarding daylight glare are to be conducted. Total time required is 15 minutes for each subject.

There are some requirements described below.

1. A typical workspace with a non-north facing window, a south-facing window is preferred. Artificial light must be off during the experiment.
2. A computer monitor.

3. A total of 25-30 subjects would be a reasonable number for statistical purpose. At least 10 subjects are needed for each computer monitor orientation: front-facing window and side-facing window.

4. A digital camera will be used to record activities.

C.2 Planning

Explain the study by instructions.

Triggers and Interview

Ask subject to perform usual task on computer screen and look at window

Measure required illuminance

Ask subject to look at window images and tell their opinion about them

Questionnaire

C.3 Instructions:

"We are conducting a study of the workplace environment. We would like to know your opinion about how you live your on daily environment. This study has three parts which will take about 15 minutes: first a 7-minute free conversation, second I will ask you to perform some task on a computer, then I will show you some images to which you will be able to react. This will take about 5 minutes. And the third part is a questionnaire. Do you have any questions?"

C.4 Trigger and Interview

Oral triggers will be used, as an informal interview to gather information and make subjects feel comfortable about the experiment. Questions to be asked are about the temporal and spatial qualities of and sensitivity to daylight (Fourmigue Jean-Marie, 1998). Examples of questions are to describe their office; a "typical day", the distribution of the breaks during the working time; the ideal office; the ideal view through an office's window; the lighting source in the room; what could be improved in their office's lighting and how. Then more specific questions regarding windows will be asked when a set of images are shown to them to lead the interviewee to bring into general his/her discourse.

C.5 Experiment

Three illuminance levels will be recorded. The test subject must have the same position with the measuring equipment, according to the calculated distance such that the results from the mathematical calculation and the subjective assessment will be comparable. More details about the discomfort glare study can be found in www.mit.edu/people/acha under publication. Subjects will be asked to perform three usual task on a computer (the same task to all subjects) and look at the window once in a while just like his/her typical work habit. Then a set of images will be presented to the subject to evaluate the preference and to give an opinion about them. The images are generated by computer codes with respect to the real space with the hope that the tool provides designs that support human behaviors. Order of images will be given with respect to score from the objective function generated by the tool, ranging from the least fit to the most fit.

C.6 Interview

C.6.1 Fact questions

Where do you come from?

Do you have a problem with eye vision? What is your eye color?

Does your workplace have a window?

How long have you been at IBM and Toronto?

What is your typical day like?

Tell me about the distribution of break during the working time.

What is your hobby?

C.6.2 Information questions

Do you know anything about light sources, such as daylight, incandescent, or fluorescent?

Tell me how you feel or what you think about those light sources.

C.6.3 Self-perception questions

How would you rank or prioritize the following environmental properties: acoustics, light, air temperature and humidity, and indoor air quality?

What would be your preferred lighting condition in your workplace?

C.6.4 Open ended and unstructured questions

Tell me about your ideal office.

Where do you imagine you would sit related to the window?

What is the window size and location?

C.7 Questionnaire

SUBJECT _________

Date _________

Time _________

OFFICE LIGHTING SURVEY

The following questions ask about your feelings and reactions to the physical environment in your workplace. Your answers are confidential, and will be used only as a part of a research effort to determine the best conditions for working people. Please fill in the questionnaire as completely as possible. If there is a question you can not answer, skip it and move to the following question.

1) As you are performing work tasks (computer work, reading) or looking around in this room, are you experiencing glare?

yes / no

2) How important is it to you to have a source of natural light (for example; a window or a skylight) in your work area?

very important 1 2 3 4 5 would rather have none

3) Estimate the glare from following items in this working situation on a scale 1-5.

Sun:

no glare at all 1 2 3 4 5 very much glare

Daylight:

no glare at all 1 2 3 4 5 very much glare

Reflections (e.g. from the monitor or other shining surfaces):

no glare at all 1 2 3 4 5 very much glare

Other (please, specify): _______

no glare at all 1 2 3 4 5 very much glare

4) If the glare is disturbing, what would you like to be done to it?

____

5) Assuming that this is your workspace, overall, how satisfied are you with the lighting at this workspace?

Very satisfied 1 2 3 4 5 not at all satisfied

6) While you are reading this paper on the screen, assess the suitability of the amount of light for computer work. The lighting here is

quite too dim 1 2 3 4 5 quite too bright

While you are reading this paper on the desk, assess the suitability of the amount of light for reading. The lighting here is

quite too dim 1 2 3 4 5 quite too bright

7) As you look around the room, assess the evenness of the lighting in the whole room comparing the lighting on different surfaces.
Lighting distribution in the room is

too even 1 2 3 4 5 too uneven

There are disturbingly great differences in lighting distribution in the room,

Where?_________

8) Assess the comfort of lighting in the room on the scale from 1 to 5

comfortable 1 2 3 4 5 uncomfortable

Comments on the lighting of the room:

____

____

9) Does the presence of daylight in your work area lead to job performance problems?

always 1 2 3 4 5 never

10) Does the presence of daylight in your work area increase your overall job satisfaction?

___Usually increase

___Sometime increase

___Have no effect

___Sometime decrease

___Usually decrease

11) **Which of the following do you think is the most serious problem caused by windows in a workplace? (check one)**

___None

___Allows area to be affected by outside temperatures

___Causes glare

___Reduces privacy

___Allows distractions to enter

___Makes the area drafty

___Other (please specify)________

12) **Do you have a window in or near by your workstation?**

___Yes (if yes, please answer the following)

___No (if no, please skip to question 18)

13) **How far would you estimate your typical work position to be from the nearest window?**

___Less than 5 feet

___5 to 15 feet

___16 to 25 feet

___more than 25 feet

14) **How often do you choose to work using the light from the window?**

___Whenever possible

___Sometimes

___Never

___Unable to control

15) How often does the sunlight coming into your work area result in glare problems?

frequently 1 2 3 4 5 never

16) Are you able to open and close or control some part of the window area??

___Yes

___No

17) If you have an opportunity to control the window and shading device, will you use this opportunity?

___Yes

___No

18) What is your age?

___Less than 20

___20-35

___36-50

___51-65

___greater than 65

19) Which sex are you?

___Male

___Female

20) How long have you been working at your present office?

___Less than 3 months

___3 months – 1 year

___1-5 years

___more than 5 years

21) Please list three major things that you like about lighting conditions in this scene:

1.
2.
3.

22) Please list three major things that you dislike about lighting conditions in this scene:

1.
2.
3.

23) Now when finished, please look at the window next to you, and rate glare perception.

___not uncomfortable

___slightly uncomfortable

___rather uncomfortable

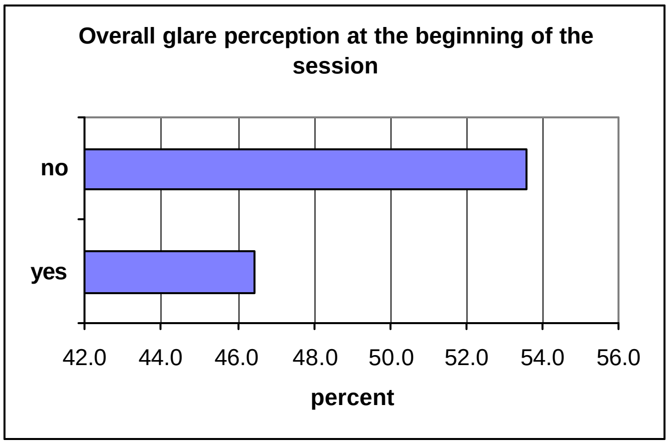
___very uncomfortable

___extremely uncomfortable

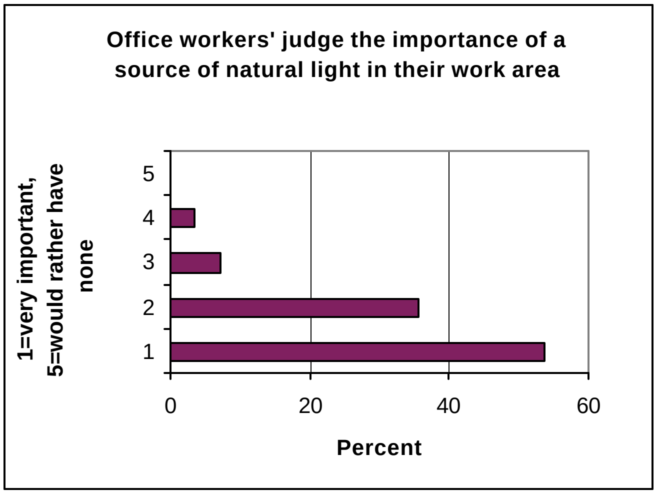
Appendix D: Data from the Experiment and Statistical Analysis

D.1 Data from the experiment

1) **As you are performing work tasks (computer work, reading) or looking around in this room, are you experiencing glare?**

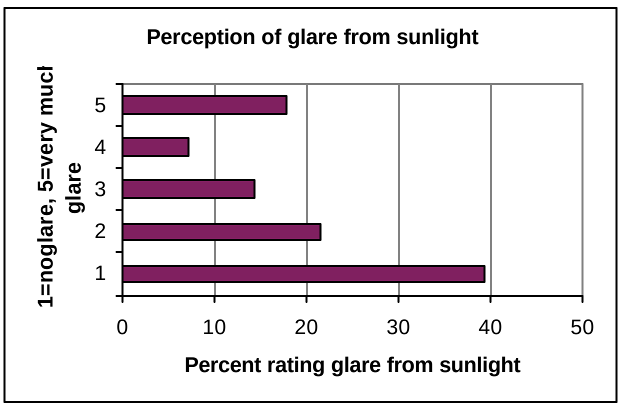


2) **How important is it to you to have a source of natural light (for example; a window or a skylight) in your work area?**

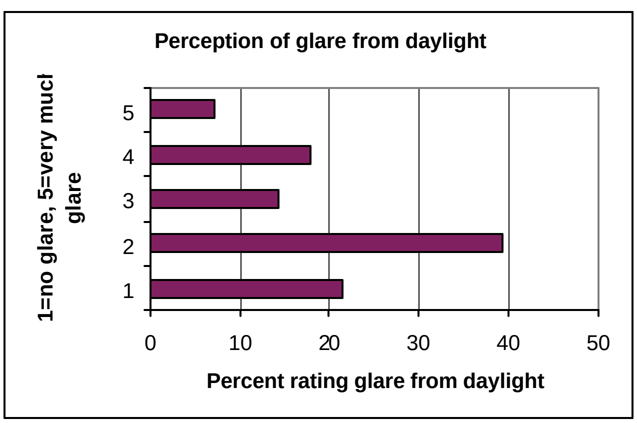


3) **Estimate the glare from following items in this working situation on a scale 1-5.**

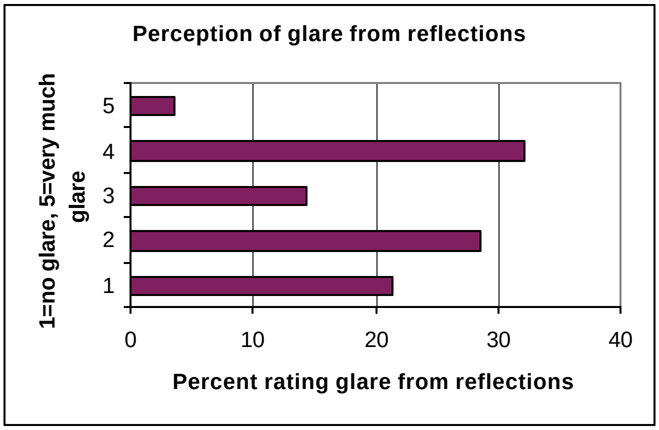
Sun:



Daylight:



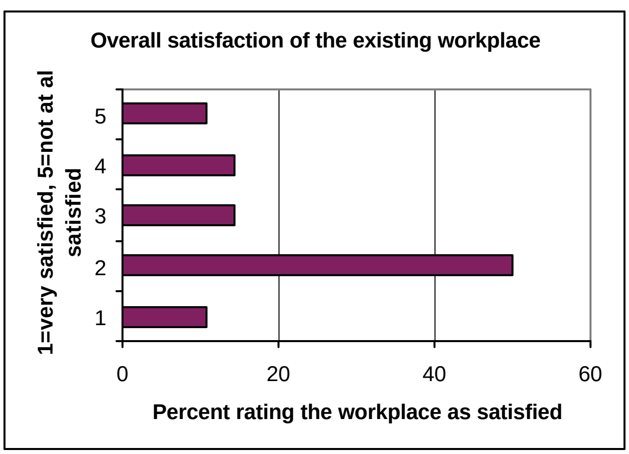
Reflections (e.g. from the monitor or other shining surfaces):



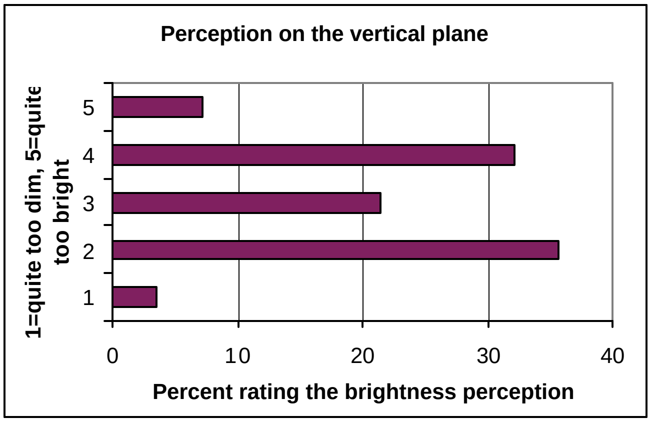
4) If the glare is disturbing, what would you like to be done to it?

____

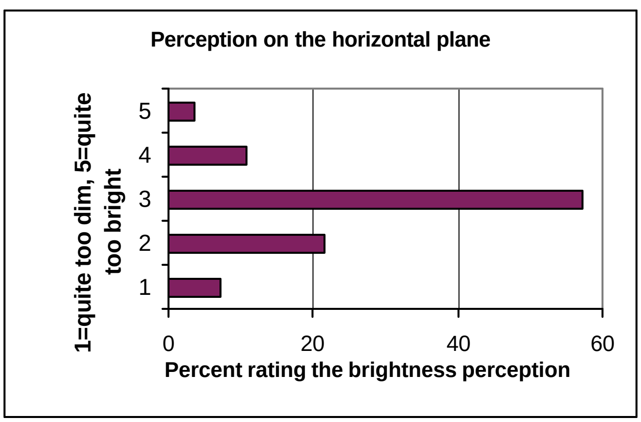
5) Assuming that this is your workspace, overall, how satisfied are you with the lighting at this workspace?



6) **While you are reading this paper on screen, assess the suitability of the amount of light for computer work. The lighting here is**

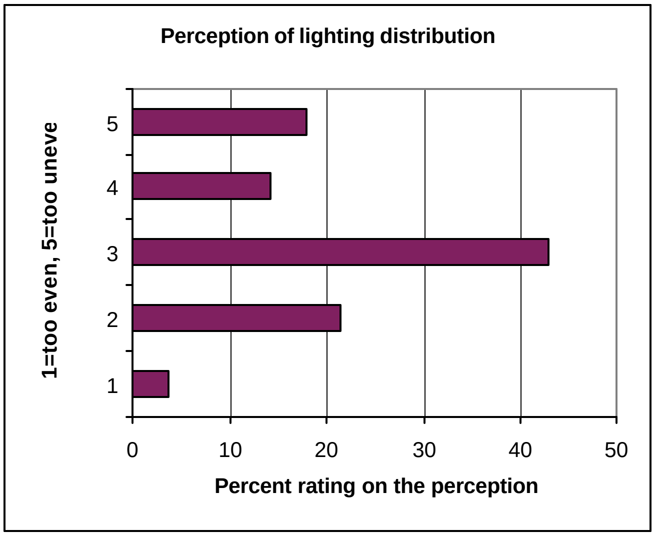


While you are reading this paper on desk, assess the suitability of the amount of light for reading. The lighting here is

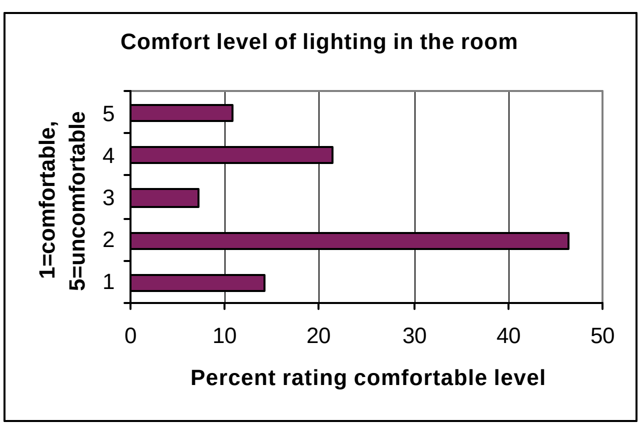


7) As you look around in the room, assess the evenness of the lighting in the whole room comparing the lighting on different surfaces.

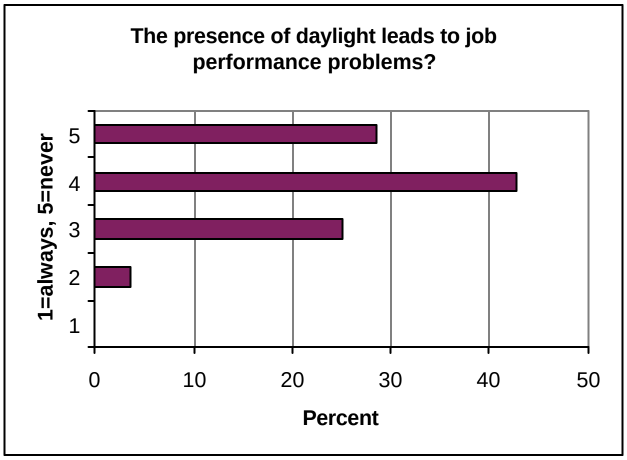
Lighting distribution in the room is



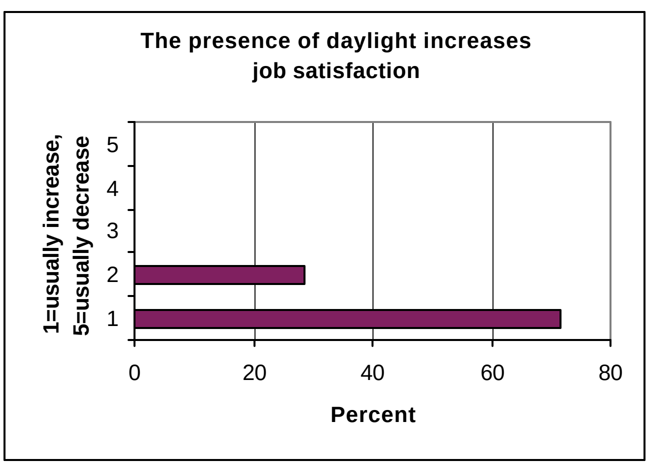
8) Assess the comfort of lighting in the room on the scale from 1 to 5



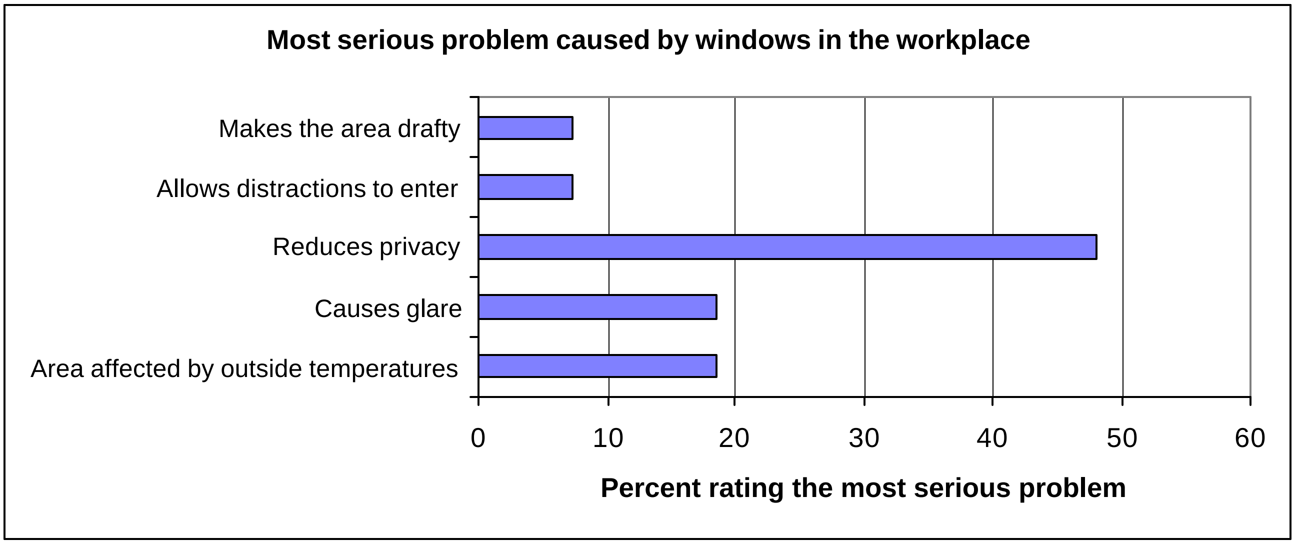
9) Does the presence of daylight in your work area lead to job performance problems?



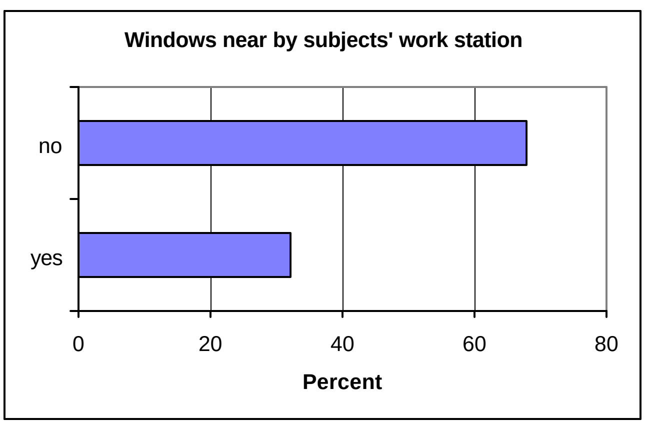
10) Does the presence of daylight in your work area increase your overall job satisfaction?



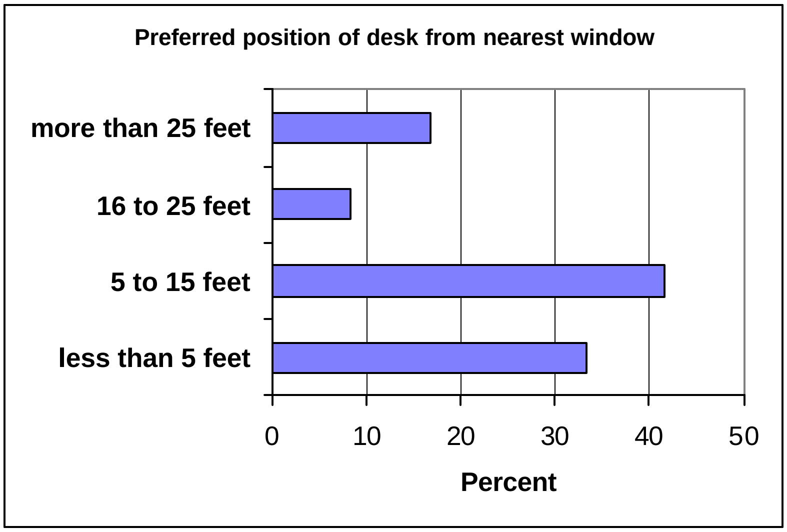
11) Which of the following do you think is the most serious problem caused by windows in a workplace? (Check one)



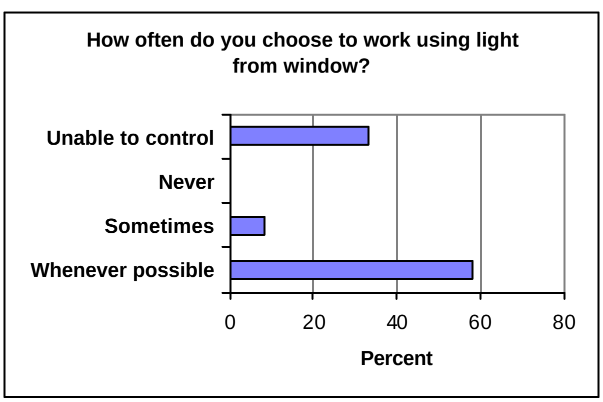
12) Do you have a window in or near by your workstation?



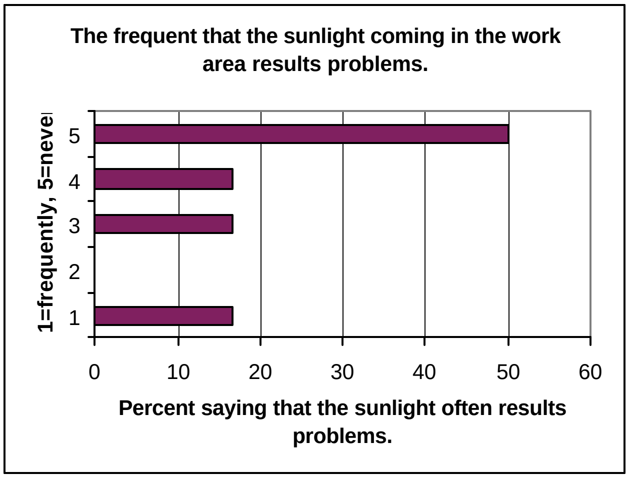
13) **How far would you estimate your typical work position to be from the nearest window?**



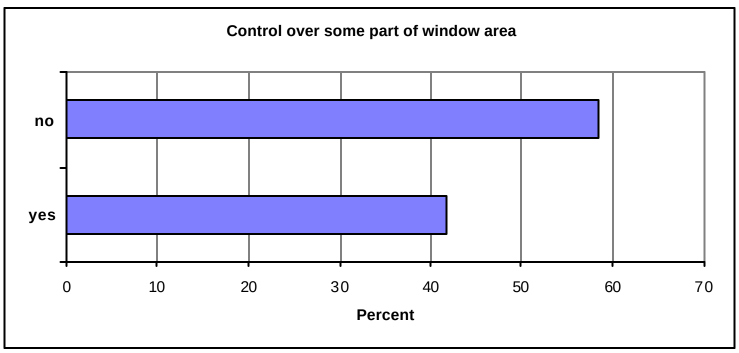
14) **How often do you choose to work using the light from the window?**



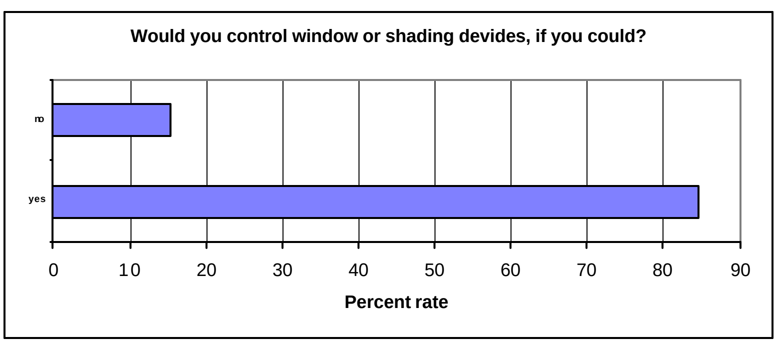
15) How often does the sunlight coming into your work area result in glare problems?



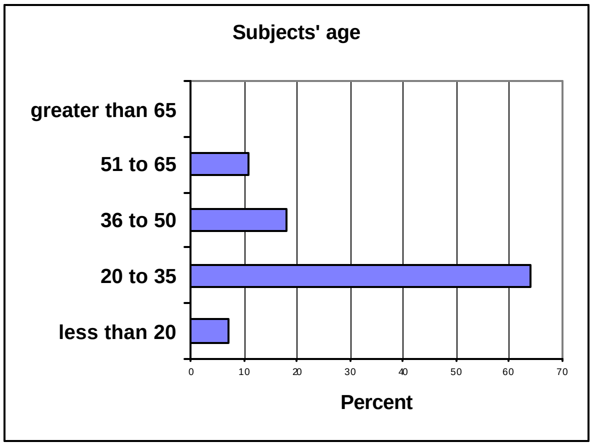
16) Are you able to open and close or control some part of the window area??



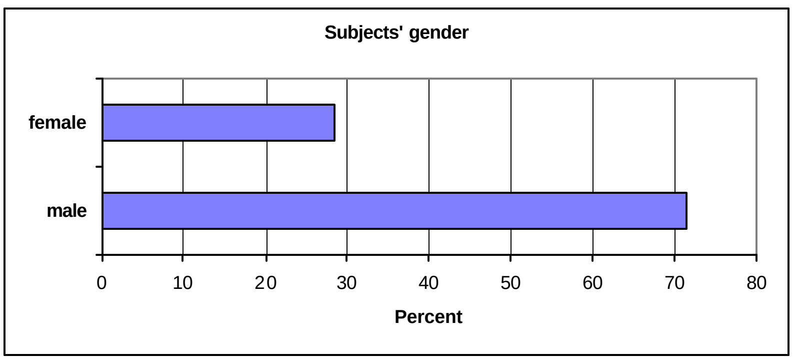
17) If you have an opportunity to control window and shading device, will you use this opportunity?



18) What is your age?



19) Which sex are you?

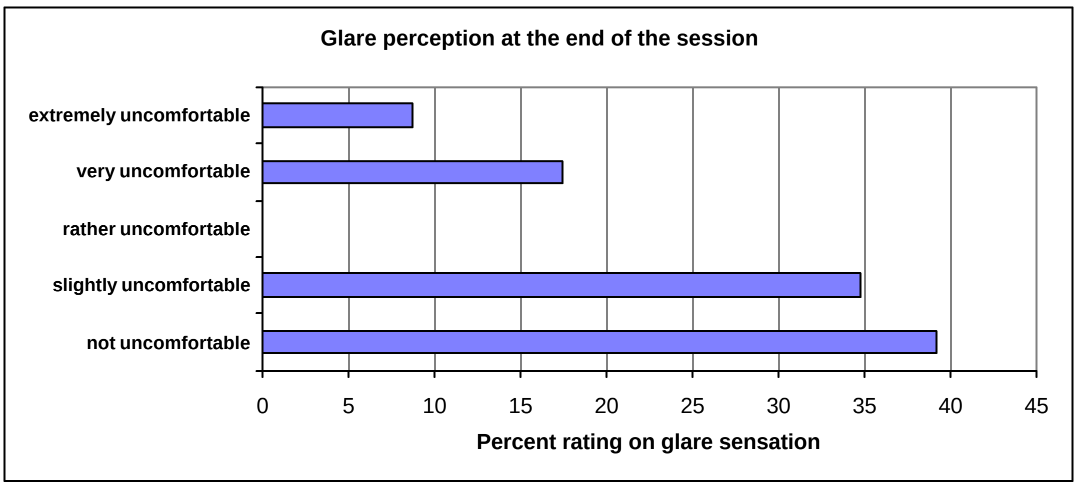


20) How long have you been working at your present office?

21) Please list three major things that you like about lighting conditions in this scene:

22) Please list three major things that you dislike about lighting conditions in this scene:

23) Now when finished, please look at the window next to you, and rate your glare perception.



D.2 Data measured during the experiment

Sub-No.	EexWin1	EexWin2	EadaptWin1	EadaptWin2	EwinWin1	EwinWin2	L-Nwall	L-Ewall	L-Wwall	L-Swall	Sky	SubFacing
1	3800	3800	1100	960	890	630	40	4100	45	48	2	1
2	3800	3800	1100	960	890	630	40	4300	45	48	2	1
3	4100	4400	1600	1400	960	1100	64	5780	55	64	2	1
4	3600	4100	960	1000	830	960	55	4000	51	55	3	1
5	3300	3600	1200	1100	1100	1000	51	4700	48	51	3	1
6	2200	2500	830	780	680	720	45	3830	51	45	2	2
7	2000	2200	630	680	780	630	34	4380	39	34	2	2
8	1200	1300	590	480	510	420	32	2700	45	29	2	2
9	31000	28000	2200	1800	1400	1400	119	5780	90	128	1	2
10	8200	8200	2000	1900	1400	1600	111	7760	84	73	3	1
11	1900	2200	960	720	630	680	42	2520	42	35	3	1
12	1800	1800	720	510	680	480	21	1650	25	14	3	2
13	6600	6600	1500	1700	1300	1600	68	5500	59	73	3	2
14	5400	5400	1700	1400	960	1300	55	4380	45	64	3	2
15	5400	5400	1700	1400	960	1300	55	4380	45	64	3	2
16	3300	3300	780	890	480	630	59	3320	51	45	2	1
17	1900	2000	720	720	630	680	42	3160	45	39	2	1
18	830	830	420	320	390	290	12	2000	13	16	3	1
19	35000	35000	2700	2200	1500	1700	222	6230	128	194	1	1
20	33000	33000	1800	1800	1400	1400	128	5780	92	157	1	2
21	31000	31000	1700	1700	1200	1300	111	5040	84	128	1	2
22	23000	23000	1500	1500	1000	1200	84	4380	68	90	1	1
23	20000	20000	1400	1400	1000	1100	78	4100	64	84	1	1
24	15000	14000	1400	1000	960	630	79	3830	68	73	1	2
25	2900	2900	720	720	510	550	39	2890	39	42	2	2
26	2900	2900	720	720	510	550	39	2892	39	42	2	2
27	2500	2500	680	550	590	440	36	2700	36	39	1	2
28	2000	2000	830	830	630	720	42	3110	45	42	1	1
29	2400	2400	630	680	420	550	36	2700	45	39	1	1

Sub-No	Subject number
EexWin1	Vertical exterior illuminance measured at the center of window 1 (Lux)
EexWin2	Vertical exterior illuminance measured at the center of window 2 (Lux)
EadaptWin1	Vertical adaptation illuminance measured at the subject's eye level (Lux)
EadaptWin2	Vertical adaptation illuminance measured at the subject's eye level (Lux)
EwinWin1	Vertical shielded illuminance measured at the pyramid at the subject's eye level (Lux)
EwinWin2	Vertical shielded illuminance measured at the pyramid at the subject's eye level (Lux)
L-Nwall	Luminance of the north wall measured at the subject's eye level (cd/m^2)
L-Ewall	Luminance of the east wall (window) measured at the subject's eye level (cd/m^2)
L-Wwall	Luminance of the west wall measured at the subject's eye level (cd/m^2)
L-Swall	Luminance of the south wall measured at the subject's eye level (cd/m^2)
Sky	Sky conditions; 1 = clear sky, 2 = partly cloudy sky, 3 = overcast sky
SubFacing	Subject orientation facing the window; 1= front facing, 2 = side facing

D.3 Converted illuminance levels to luminance levels using the new DGI_n method

Lex	Ladp	Lwin	DGIN	R-Q23
888	350	753	22	*
888	350	753	22	*
958	510	813	21	*
841	306	703	22	*
771	382	931	21	*
514	264	576	19	1
467	201	660	19	1
280	188	432	16	2
7243	701	1185	34	4
1916	637	1185	25	1
444	306	533	18	2
421	229	576	18	2
1542	478	1100	25	4
1262	541	813	23	4
1262	541	813	23	2
771	248	406	22	1
444	229	533	19	5
194	134	330	15	1
8178	860	1270	34	1
7710	573	1185	35	1
7243	541	1016	35	2
5374	478	847	34	2
4673	446	847	33	4
3505	446	813	31	2
678	229	432	22	2
678	229	432	22	*
584	217	499	21	1
467	264	533	19	5
561	201	356	21	1

Legend

Lex	Vertical exterior luminance (cd/m²)
Ladp	Adaptation luminance (cd/m²)
Lwin	Window luminance (cd/m²)
DGIN	The new Daylight Glare Index
R-Q23	Respond to question number 23

D.4 Analysis of Variance (ANOVA) and PEARSON Correlations

Information presented below has been derived from Minitab R12 using ANOVA analysis and Pearson correlations for Q.23 and Q.1 or glare perception before and after the session.

One-way Analysis of Variance

Analysis of Variance for R-Q23

Source	DF	SS	MS	F	P
EwinWin1	13	24.75	1.90	1.00	0.516
Error	9	17.17	1.91		
Total	22	41.91			

One-way Analysis of Variance

Analysis of Variance for R-Q23

Source	DF	SS	MS	F	P
EwinWin2	13	16.58	1.28	0.45	0.905
Error	9	25.33	2.81		
Total	22	41.91			

One-way Analysis of Variance

Analysis of Variance for R-Q23

Source	DF	SS	MS	F	P
Leastwal	**15**	**31.50**	**2.10**	**1.41**	**0.334**
Error	7	10.42	1.49		
Total	22	41.91			

One-way Analysis of Variance

Analysis of Variance for R-Q23

Source	DF	SS	MS	F	P
SkyCondi	2	0.38	0.19	0.09	0.912
Error	20	41.53	2.08		
Total	22	41.91			

One-way Analysis of Variance

Analysis of Variance for R-Q23

Source	DF	SS	MS	F	P
SubjectF	1	0.12	0.12	0.06	0.808
Error	21	41.79	1.99		
Total	22	41.91			

One-way Analysis of Variance

Analysis of Variance for R-Q1

Source	DF	SS	MS	F	P
EwinWin1	15	4.131	0.275	1.17	0.400
Error	12	2.833	0.236		

Total	27	6.964			

One-way Analysis of Variance

Analysis of Variance for R-Q1

Source	DF	SS	MS	F	P
EwinWin2	14	2.931	0.209	0.67	0.763
Error	13	4.033	0.310		
Total	27	6.964			

One-way Analysis of Variance

Analysis of Variance for R-Q1

Source	DF	SS	MS	F	P
Leastwal	**18**	**5.048**	**0.280**	**1.32**	**0.346**
Error	9	1.917	0.213		
Total	27	6.964			

One-way Analysis of Variance

Analysis of Variance for R-Q1

Source	DF	SS	MS	F	P
SkyCondi	2	0.242	0.121	0.45	0.643
Error	25	6.722	0.269		
Total	27	6.964			

One-way Analysis of Variance

Analysis of Variance for R-Q1

Source	DF	SS	MS	F	P
SubjectF	1	0.036	0.036	0.13	0.717
Error	26	6.929	0.266		
Total	27	6.964			

Current worksheet: Skyclear.MTW

Correlations (Pearson)

	EexWin1	EadaptWi	EwinWin1	Leastwal	R-Q1	R-Q23
EadaptWi	0.927					
	0.000					
EwinWin1	0.972	0.959				
	0.000	0.000				
Leastwal	0.973	0.963	0.986			
	0.000	0.000	0.000			
R-Q1	**-0.516**	**-0.523**	**-0.576**	**-0.596**		
	0.155	0.149	0.105	0.090		
R-Q23	**-0.130**	**-0.064**	**-0.050**	**-0.080**	**-0.594**	
	0.720	0.860	0.891	0.825	0.092	

DGIN	0.939	0.821	0.886	0.852	**-0.345**	**-0.103**
	0.000	0.004	0.001	0.002	0.363	0.778

Cell Contents: Correlation
P-Value

Current worksheet: Skypc.MTW

Correlations (Pearson)

	EexWin1	EadaptWi	EwinWin1	Leastwal	R-Q1
EadaptWi	0.801				
	0.005				
EwinWin1	0.556	0.786			
	0.095	0.007			
Leastwal	0.587	0.846	0.897		
	0.074	0.002	0.000		
R-Q1	**0.274**	**0.271**	**-0.080**	**0.070**	
	0.444	0.449	0.826	0.847	
R-Q23	**-0.310**	**-0.115**	**-0.054**	**-0.423**	**-0.250**
	0.550	0.828	0.918	0.403	0.633

Cell Contents: Correlation
P-Value

Current worksheet: Skyoc.MTW

Correlations (Pearson)

	EexWin1	EadaptWi	EwinWin1	Leastwal	R-Q1	R-Q23
EadaptWi	0.942					
	0.000					
EwinWin1	0.919	0.858				
	0.000	0.003				
Leastwal	0.934	0.866	0.932			
	0.000	0.003	0.000			
R-Q1	**-0.029**	**0.163**	**0.100**	**-0.193**		
	0.941	0.675	0.797	0.619		
R-Q23	**0.302**	**0.318**	**0.337**	**0.119**	**0.701**	
	0.510	0.486	0.460	0.800	0.080	
DGIN_1	0.950	0.903	0.927	0.879	**0.097**	**0.470**
	0.000	0.001	0.000	0.002	0.804	0.287

Cell Contents: Correlation
P-Value

Current worksheet: Skyclearfront.MTW

Correlations (Pearson)

	EexWin1	EadaptWi	EwinWin1	Leastwal	R-Q1	R-Q23
EadaptWi	0.954					
	0.012					
EwinWin1	0.971	0.982				
	0.006	0.003				
Leastwal	0.965	0.998	0.988			
	0.008	0.000	0.001			
R-Q1	**0.088**	**-0.068**	**-0.211**	**-0.047**		
	0.912	0.932	0.789	0.953		
R-Q23	**-0.396**	**-0.387**	**-0.253**	**-0.372**	**-0.949**	
	0.509	0.520	0.681	0.538	0.051	
DGIN	0.928	0.776	0.842	0.801	**0.110**	**-0.303**
	0.023	0.123	0.073	0.103	0.890	0.620

Cell Contents: Correlation
P-Value

Current worksheet: Skyclearside.MTW

Correlations (Pearson)

	EexWin1	EadaptWi	EwinWin1	Leastwal	R-Q1	R-Q23
EadaptWi	0.924					
	0.025					
EwinWin1	0.975	0.964				
	0.005	0.008				
Leastwal	0.979	0.953	0.996			
	0.004	0.012	0.000			
R-Q1	**-0.941**	**-0.831**	**-0.893**	**-0.927**		
	0.017	0.082	0.041	0.023		
R-Q23	**0.406**	**0.691**	**0.483**	**0.469**	**-0.373**	
	0.498	0.196	0.410	0.425	0.537	
DGIN	0.356	0.635	0.473	0.482	**-0.408**	**0.913**
	0.556	0.250	0.421	0.411	0.495	0.030

Cell Contents: Correlation
P-Value

Current worksheet: Skypcfront.MTW

Correlations (Pearson)

	EexWin1	EadaptWi	EwinWin1	Leastwal	R-Q1	R-Q23
EadaptWi	0.774					
	0.124					
EwinWin1	0.651	0.840				
	0.234	0.075				
Leastwal	0.752	0.997	0.819			
	0.143	0.000	0.090			
R-Q1	**0.552**	**0.392**	**0.044**	**0.439**		
	0.334	0.514	0.943	0.459		
R-Q23	**-1.000**	**-1.000**	**1.000**	**-1.000**	**-1.000**	
	*	*	*	*	*	
DGIN	0.814	0.263	0.215	0.233	**0.490**	-1.000
	0.093	0.669	0.729	0.706	0.402	*

Cell Contents: Correlation
P-Value

Current worksheet: Skypcside.MTW

Correlations (Pearson)

	EexWin1	EadaptWi	EwinWin1	Leastwal	R-Q1	R-Q23
EadaptWi	0.577					
	0.308					
EwinWin1	-0.201	0.087				
	0.746	0.889				
Leastwal	-0.095	0.159	0.994			
	0.880	0.798	0.001			
R-Q1	**-0.245**	**-0.422**	**-0.640**	**-0.678**		
	0.692	0.480	0.245	0.209		
R-Q23	**-0.041**	**-0.406**	**-0.952**	**-0.954**	**0.577**	
	0.959	0.594	0.048	0.046	0.423	
DGIN	0.994	0.488	-0.209	-0.105	**-0.218**	**0.000**
	0.001	0.405	0.735	0.867	0.724	1.000

Cell Contents: Correlation

P-Value

Current worksheet: Skyocfront.MTW

Correlations (Pearson)

	EexWin1	EadaptWi	EwinWin1	Leastwal	R-Q1	R-Q23
EadaptWi	0.961					
	0.009					
EwinWin1	0.922	0.954				
	0.026	0.012				
Leastwal	0.983	0.960	0.967			
	0.003	0.009	0.007			
R-Q1	**-0.313**	**-0.044**	**-0.012**	**-0.236**		
	0.608	0.943	0.985	0.703		
R-Q23	**-0.379**	**-0.180**	**-0.290**	**-0.428**	**1.000**	
	0.752	0.885	0.813	0.719	*	
DGIN	0.925	0.907	0.938	0.926	**-0.167**	**-0.225**
	0.025	0.034	0.018	0.024	0.789	0.856

Cell Contents: Correlation
P-Value

Current worksheet: Skyocside.MTW

Correlations (Pearson)

	EexWin1	EadaptWi	EwinWin1	Leastwal	R-Q1	R-Q23
EadaptWi	0.887					
	0.113					
EwinWin1	0.918	0.631				
	0.082	0.369				
Leastwal	0.999	0.862	0.937			
	0.001	0.138	0.063			
R-Q1	*	*	*	*		
	*	*	*	*		
R-Q23	**0.667**	**0.483**	**0.705**	**0.678**	*	
	0.333	0.517	0.295	0.322	*	
DGIN	0.999	0.865	0.935	1.000	*	**0.677**
	0.001	0.135	0.065	0.000	*	0.323

Cell Contents: Correlation
P-Value