

# A New Design Process Using an Inverse Method: A Genetic Algorithm for Daylighting Design

## ขั้นตอนการออกแบบแบบแนวใหม่โดยใช้วิธีการผกผัน:

### การหาค่าพอดีสำหรับการออกแบบแบบแสงสว่างธรรมชาติด้วยกระบวนการคำนวณทางพัณฑุกรรม

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#### Abstract

Today, architectural design emphasizes high-standard buildings with sophisticated daylighting systems, because harnessing daylight provides both energy savings on lighting and psycho-physical comfort in room space. Daylighting design is a hard problem since its properties—such as lighting intensity and distribution, colors and radiant energy—vary over time. Most problem-solving techniques are forward method and are typically “trial and error” process, attacking problems on the front end first. On the other hand, a problem-solving technique called the inverse method, which seems to be efficient, has been applied in this paper. The paper emphasizes the use of scientific-knowledge computational tools in the later stages of design in an effort to provide optimum choices of design. Genetic algorithm (GA) is used to search for optimal design strategies. A new design process has been created and implemented to increase design process efficiency. In addition to the architectural representation, this paper presents a structured method for defining and evaluating multiple objectives. Lightshelf and its daylighting system parameters are under investigation. Moreover, this work investigated several design problems, GA parameters and processes for improving design results. Results show that a new model using basic genetic algorithm techniques results in shorter design times and greater diversity of solutions.

#### บทคัดย่อ

งานสถาปัตยกรรมในยุคปัจจุบันเน้นการออกแบบอาคารที่มีคุณภาพ และยังคำนึงถึงการใช้ประโยชน์จากแสงสว่างธรรมชาติ เนื่องจากความต้องการสำหรับการใช้ในอาคาร นำมาซึ่งการประยุกต์พัฒนาจากการให้หลอดไฟ ถือทั้งยังตอบสนองความต้องการของมนุษย์ในเชิงจิตวิทยา อย่างไรก็ตาม การนำแสงสว่างธรรมชาติเข้ามายังในอาคารเป็นเรื่องที่ยากมาก เพราะเหตุว่าแสง สี การส่องสว่างและพัฒนาของดวงอาทิตย์นั้นเปลี่ยนแปลงไปตลอดเวลา วิธีการแก้ปัญหาที่สถาปนิกใช้กันอยู่ในปัจจุบันทั่วไป เป็นวิธีการแก้ปัญหาที่สามารถจัดได้จากเครื่องข่ายของการทดลองผิดลองถูก สถาปนิกเริ่มต้นจากการออกแบบ และเมื่อนำไปประเมินผลของการออกแบบแล้วผลลัพธ์ไม่เป็นไปตามจุดประสงค์ก็กลับมาแก้ไขงานออกแบบ วนอย่างนี้เรื่อยไปจนได้ผลงานที่สอดคล้องกับจุดมุ่งหมาย ในทางตรงกันข้าม วิธีการแก้ปัญหาอีกแบบหนึ่งที่เป็นวิธีการแปรผกผันกันด้วยการเริ่มต้นจากการออกแบบ และกำหนดจุดประสงค์ที่ต้องการพร้อมกันในขั้นแรกของกระบวนการออกแบบที่เรียกว่า “Inverse Method” ซึ่งน่าจะเป็นวิธีที่มีประสิทธิภาพสูง โดยได้มีการนำเสนอ ศึกษา และประยุกต์ในงานวิจัยฉบับนี้ ผลงานนี้รวมเทคโนโลยีในสาขาต่าง ๆ มา

ประดิษฐ์และประกอบกันขึ้นเป็นโปรแกรมคอมพิวเตอร์ซึ่งเป็นเครื่องช่วยในการออกแบบ โดยมีเป้าหมายที่จะเสนอรูปแบบอาคาร หลาຍ ๆ รูปแบบที่เหมาะสมและสอดคล้องกับความต้องการทางด้านปรากฏการณ์ของแสงในอาคาร งานวิจัยนี้ศึกษากระบวนการคำนวณทางพันธุกรรม (Genetic Algorithm, GA) ในงานสถาปัตยกรรม GA เป็นเครื่องมือที่ใช้ในวิัฒนาการหารูปแบบอาคาร หรือผลลัพธ์ของการออกแบบได้อย่างมีประสิทธิภาพ นอกจากที่ผู้แต่งได้นำเสนอวิธีการประยุกต์ใช้ GA แล้ว ยังได้มีการยกตัวอย่าง และพิสูจน์สมรรถภาพของแนวความคิดและโปรแกรมคอมพิวเตอร์นี้ โดยได้ทำการศึกษา Lightshelf หรือแผงบังและสะท้อนแสงเดด รวมทั้งปัจจัยอื่นๆ ที่เอื้ออำนวยให้แสงธรรมชาติส่องในอาคารในปริมาณที่ต้องการ ผลการวิจัยสรุปได้ว่า แนวทางในการประยุกต์ใช้วิธีการผกผัน และ GA สามารถพัฒนาผลของการออกแบบได้ดี และช่วยในการตัดสินใจของผู้ออกแบบภายในระยะเวลาที่เร็ว กว่า เมื่อเทียบกับการแก้ปัญหาแบบลองผิดลองถูก

#### Keywords (คำสำคัญ)

Daylighting (การให้แสงสว่างธรรมชาติ)

Genetic Algorithm (กระบวนการคำนวณทางพันธุกรรม)

Optimization (การหาค่าที่พอดี)

Design Process (ขั้นตอนการออกแบบ)

Inverse Method (วิธีการผกผัน)

## Introduction

Integration of daylight availability in time and architectural space is a critical element in achieving comfort and productivity, as well as in minimizing energy consumption. There are many problem-solving techniques associated with daylighting delivery systems. Most popular techniques are forward method, attacking problems on the front end first. On the other hand, a problem-solving technique called the inverse or backward method, which is very efficient, has not been applied in architectural design. This method starts with designer's goals and identifies a design to meet those goals.

The expanding demand for accommodation and an interdisciplinary product results in an enlargement of both the scale and complexity of building projects. The problem associated with the traditional design process is that it is a process of trial and error. It is therefore repeated until a desirable design is achieved. In order to achieve better design quality and expand the range of creative design options, the design process and its tools need to be analyzed and developed.

This research emphasizes the use of scientific-knowledge computational tools in the later stages of design in an effort to provide optimum choices of daylighting design with respect to light level and visual comfort using an inverse method. In this study, lightshelf and its related parameters are the daylighting system under investigation. With this method, any rectangular rooms, windows, and lightshelves may be optimized. This work establishes a genetic language and implements its principles through a number of architectural variables for finding optimal solutions. In

addition to the architectural representation, this work presents a structured method for defining and evaluating multiple objectives.

Specifically, the objectives of this research are as follows:

- To provide a new design approach to daylighting design problems using an inverse method.
- To implement and describe architectural representations in terms of genetic language through an example of work in lightshelf design. A new system model and its application will be created, which allows a user to evolve solutions and images on computer graphic user interfaces.
- To develop an objective function for daylighting design and test whether the objective function is valid.
- To present results and to analyze a daylighting design system.

## Traditional Design Processes and Tools

One major problem is that software tools currently available to designers are based on traditional design processes or direct methods. To estimate the performance of building designs, these processes force a designer to begin with the building geometry, and window properties; the processes, and then simulate a solution and its performance. The process is repeated until the solution closes to the desired effect. Most lighting analysis tools such as Lumen Micro, ADELIN, Lightscape, etc., do not directly help in the design decision process; rather, they are used to evaluate existing design or determine will-be performance of the design. It is a trial and error process, which is limited by the nonuse of directional information.

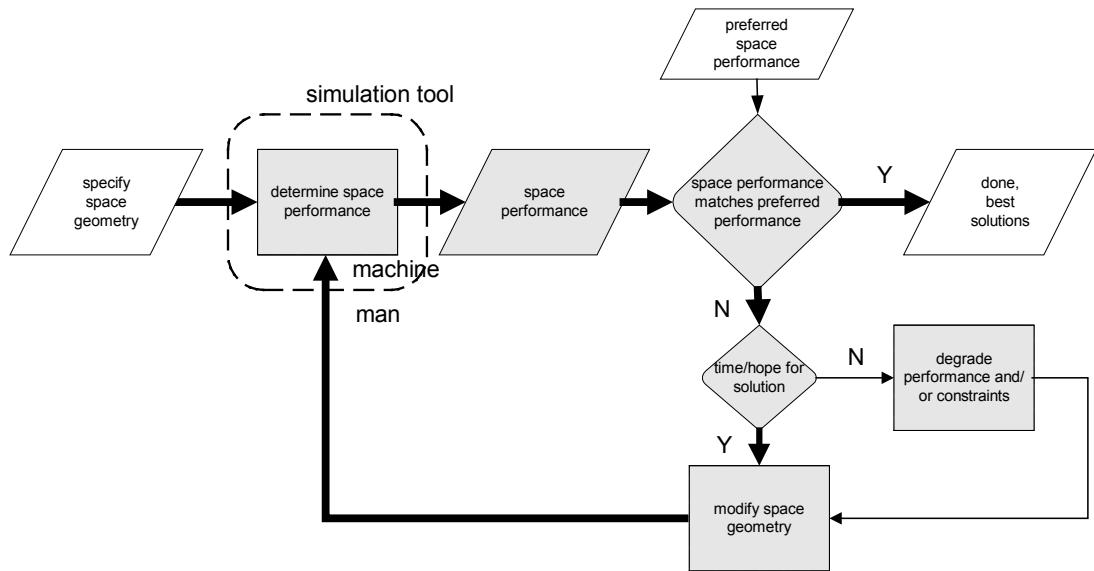


Figure 1 Traditional role of man and machine in the design process

### An Inverse Method

An inverse method is a problem-solving technique that begins to attack a problem at the end. When a particular solution state is clearly defined, a problem can be solved by starting with the solution

and working backwards toward the problem. This approach allows the user to create a target performance and preferred space geometry, and work backward to obtain the optimum parameters [1].

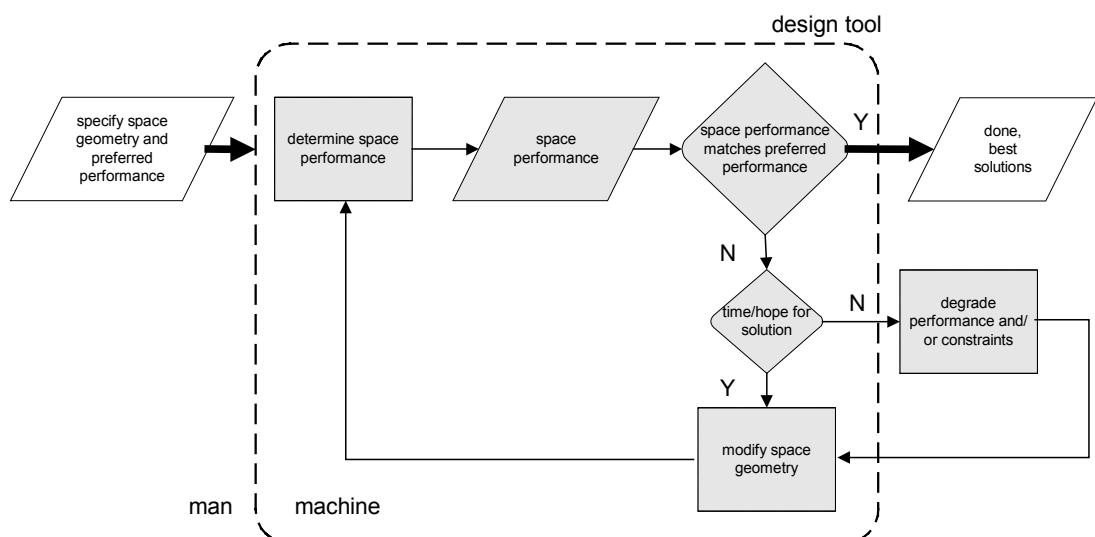


Figure 2 Role of man and machine in the design process using an inverse method

## A New Approach to Problem-solving Techniques and Searching Methods in Daylighting 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 forms and human needs [2].

### Daylighting Design Criteria

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. People's aesthetic judgments are determined primarily by the perceived brightness and color of the overall space. In designing a good visual environment, it is important to consider that the way in which surfaces are illuminated and how this affects visual perception, is more important than the amount of light that strikes them. Design quality and quantity criteria used in this research are daylighting glare index and lighting level. The other issues—such as patterns of shadow, visual noise, and color rendering—are left for designers in making their decisions. The glare

perception and illuminance levels are the most crucial criteria, since they strongly affect visual perception and performance.

### Assumptions

Several assumptions are made to limit and simplify the problems and make them more manageable, since a problem with no presuppositions becomes too broad for practical analysis or resolution. The scope of this study is to evaluate the effect of utilizing lightshelf daylighting delivery systems in interior space. It encompasses only visual quality and visual quantity issues. It does not include cost-effectiveness and other building performance aspects, such as thermal comfort. Further, this study will be limited to the following:

- The system is assumed for use in later stages of the design process, in which room dimensions are fixed during the optimization process.
- The sky condition can be either clear sky or overcast sky.
- The glare evaluation method included in this study is discomfort glare, as represented by the modified Daylight Glare Index (DGI) developed by Nazzal and the author [3].
- Glare view is fixed to the center of the window, which is the worst case.

### Algorithm

Figure 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

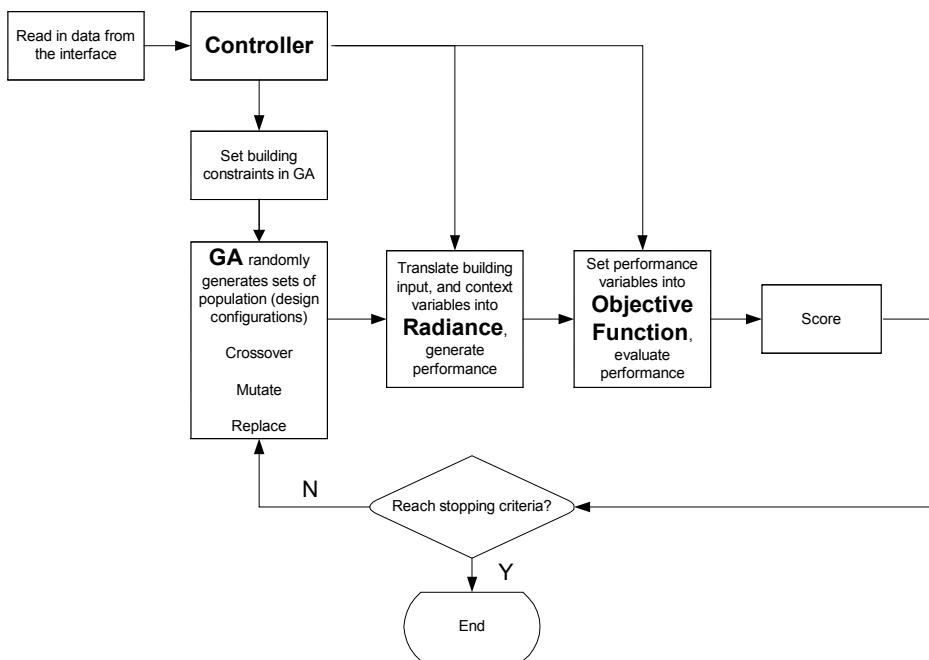


Figure 3 General optimization system architecture and process

(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. Once all data have been entered, the controller transforms the variables into GA parameters and also generates an objective function. 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 lighting level and glare. Then the outputs are evaluated with regard to the objective function created by the main script. 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 loop continues until it meets stopping criteria.

### Objective Function

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.

Equation 1 is a general optimization formula. 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

$$\text{Minimize } P_{obj} = \frac{\sum_{i=1}^m w_i f_i}{\sum_{i=1}^m w_i} \quad (1)$$

Where  $f$  = fitness score for light and glare level  
 $w$  = weighting factor

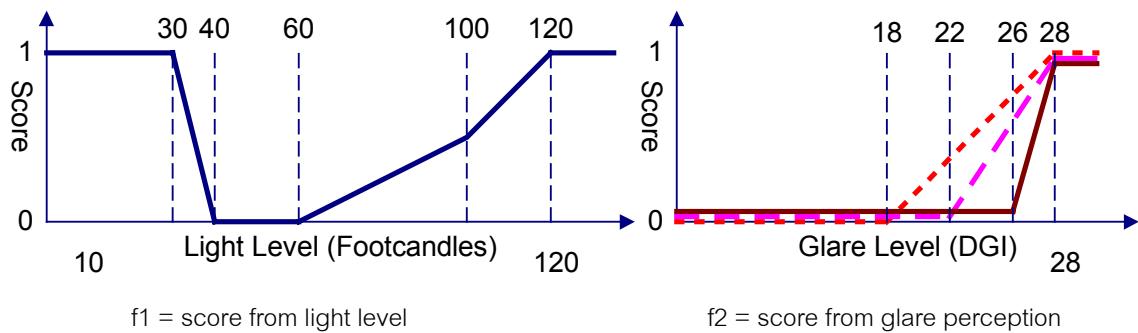


Figure 4 Example of performance variables and constraints employed in this research

penalized in proportion to their effects on an end user's experience. Figure 4 illustrates how different preferred values are penalized. It shows that preferred light level falls into a range of 40 to 60 footcandles which provides score of 0.

The three curves presented in Figure 4 are adapted from the IESNA recommended DGI (Daylighting Glare Index) 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, and 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.

#### Optimization Tool

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 5 shows a result from an exhaustive test, illustrating a solution space for finding the best lightshelf depth and height for a south-facing window.

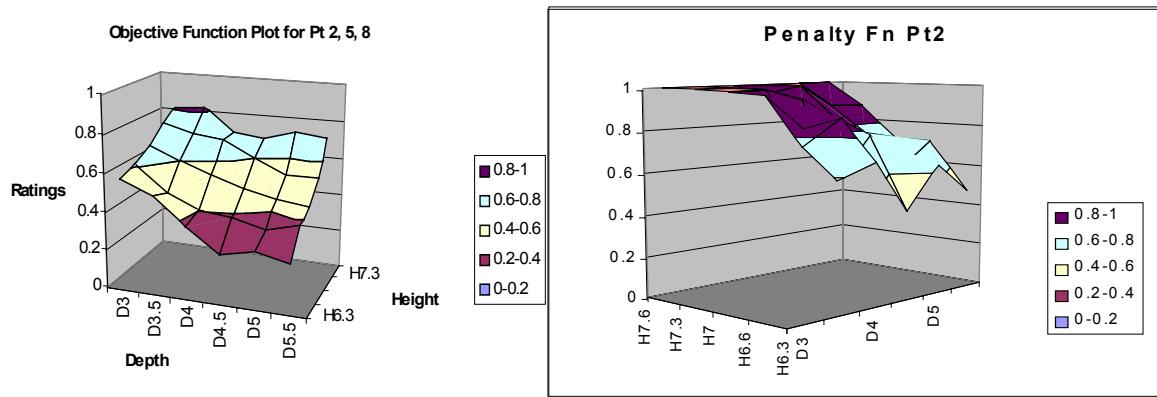


Figure 5 Ratings for lightshelf depth and height

An objective is to achieve the desired lighting level of 50 footcandles at three different points in a room: front, center, and back. In this case, The lower the rating score, the better the solution.

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 objective functions encountered in the context of daylighting design optimization have multiple minima shown in Figure 5 as an example. Thus a global searching method is required.

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 [4, 5]. Furthermore, they are effective for searching large and multidimensional spaces, since they operate on a population of solutions rather than on one individual case, and use no gradient method. For these reasons, GA is chosen to perform solution searches for the architectural problem presented in this research.

### Search Method (GA)

Genetic algorithms mimic the processes of natural evolution that were originally proposed as a general model of adaptive processes [6]. 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 in Figure 6.

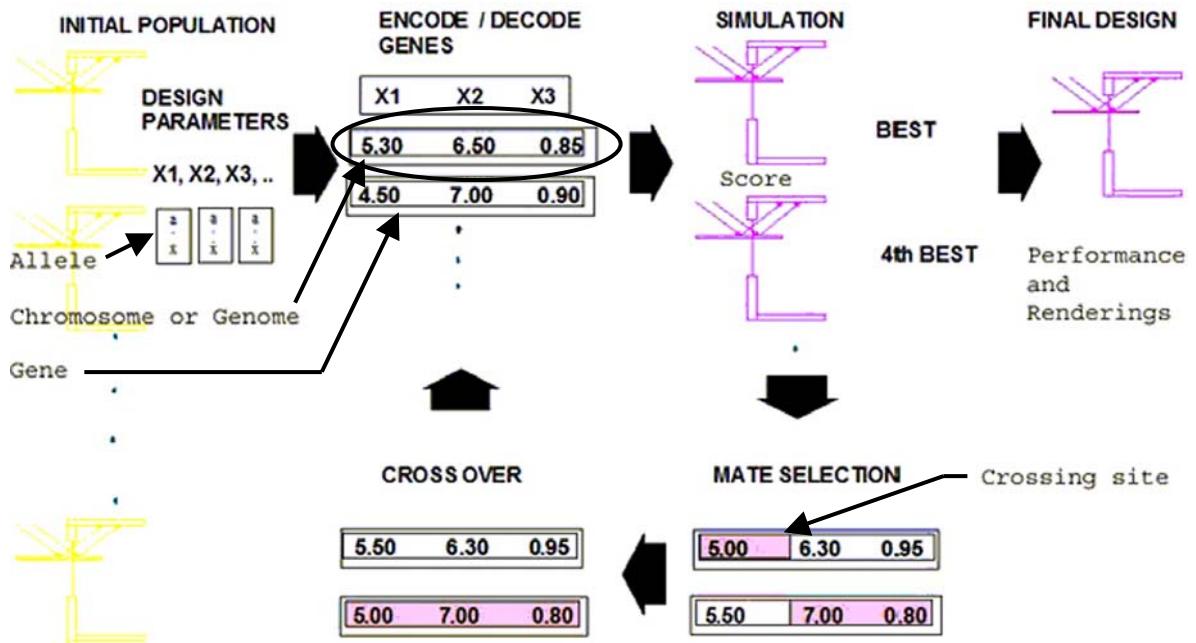


Figure 6 General GA processes

The following is a description of how to map the genetic analogy in design.

- 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, 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 genepool, which is adapted to environment of the interaction. In this case, environment represents user-response, or the interaction of a lighting designer.

A Genetic Algorithm program written by Wall in C language is chosen for this research because of its accuracy and flexibility. The following sections explain the steps and rules of the genetic algorithms [12].

- *Create Initial Population.* Populations of genomes, or sets of window variables, are randomly generated to create an initial population specified by a designer.
- *Select Parents.* Each set of configurations or individual has a fitness value, which is a measure of the quality of the solution. 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 for a longer time and generate offspring.
- *Crossover.* After two parents are selected, crossover is performed on the parents to create two offspring, or genomes. At this stage, parents

pass segments of their own genes on to their children.

- *Mutation.* The crossover may produce an offspring that does not solve a particular problem, since crossover only exploits current gene potentials. The most common way of mutating is to flip a bit with a probability equal to a given mutation rate [7]. 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 by two. To maintain a constant population size, two individuals will be eliminated from the population.
- *Terminate.* The termination function determines when the GA should stop evolving. This research uses two forms of stopping criteria: if the system finds a solution, then stops; and if the system reaches a certain generation, then the algorithm stops.

### Lighting Simulation Tool

Daylighting simulations are performed using Radiance. Radiance is a free Unix software package that adopts a radiosity-type approach to lighting simulation from Lawrence Berkeley National Laboratory. Radiance is chosen for the lighting simulation engine for several reasons.

- It is a physically based lighting program to allow accurate calculation of luminance/illuminance;
- It has the capacity to model complex geometry;
- It supports a wide variety of reflection and transmission models;

- It can link scene description input and output to CAD programs;
- The program opens to the public.

### Studies of Lightshelves

The objective of the lightshelf is to manipulate sunlight in terms of both its light and heat. If designed properly, a lightshelf should redirect sunlight or daylight onto the ceiling, enhancing lighting conditions in the space. It should improve the distribution of light and reduce glare. In a study conducted by Aizlewood [8], lightshelves were found to be the simplest and the most efficient daylighting systems, compared to prismatic glazing, mirrored louvers, and prismatic film systems. Most research studies on lightshelves were conducted employing measurements of full-scale models. Thus, only a few parameters can be investigated, since there are limitations due to the difficulty of installation and time variations. Existing studies of lightshelves by Littlefair [9, 10] and Lam [11] are used as a fundamental framework for this research. The results from this work are then compared to the existing studies as commented upon in the simulation section.

Regarding their recommendations, the variables such as lightshelf reflectance, position, size, and window parameters are to be investigated under conditions of different room geometry, orientation, and location. However, some information is useful in constructing the framework of this research. For instance, the level of the lightshelf height shall not be lower than 6' in order to avoid the direct glare. The reflectance of the shelf should not be specular, due to its thermal impact and high maintenance requirements.

## Exploration and investigation

This research 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 explore and investigate lightshelf and window parameters regarding the proposed objective function—light levels and new glare index.

In the first study, the location for the testing was Boston, Massachusetts, on June 21 at 12.00 p.m. Steady State GA, with the population size of 10, was tested against the exhaustive test, the results of which are shown in Figure 5. The room and window dimensions and measurement points are illustrated in

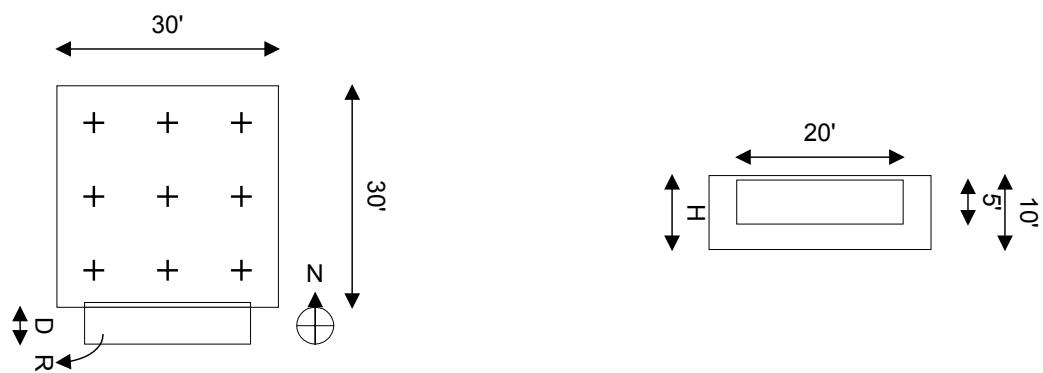


Figure 7 Room and window dimensions (not to scale)

Figure 7. 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.

To simplify the study, the only objective function ( $f_1$ ) is to achieve 50 foot-candles or 500 lux in the center of the room on the work plane, 2.5' above the floor. The results from this exhaustive study are shown in Figure 8. Stated in the objective function, the lower the fitness values, the better the performance. 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.

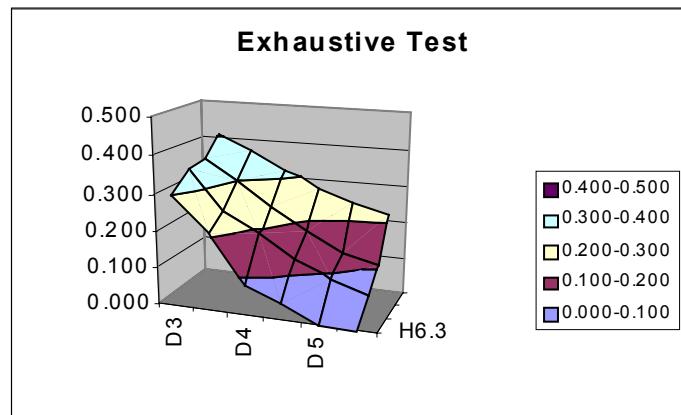


Figure 8 Fitness values corresponding to lighting levels

In the second study, Steady State GA was tested against Deterministic Crowding GA using the same set of room configurations. More detail on these algorithms can be found at <http://lancet.mit.edu/galib> [12]. 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 9 illustrates that the Deterministic Crowding GA performs better than the Steady State

GA since the Deterministic Crowding GA converges faster. Besides, it provides more design solutions than the Steady State GA. The third study, numbers of population size was 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 a better chance to find solutions.

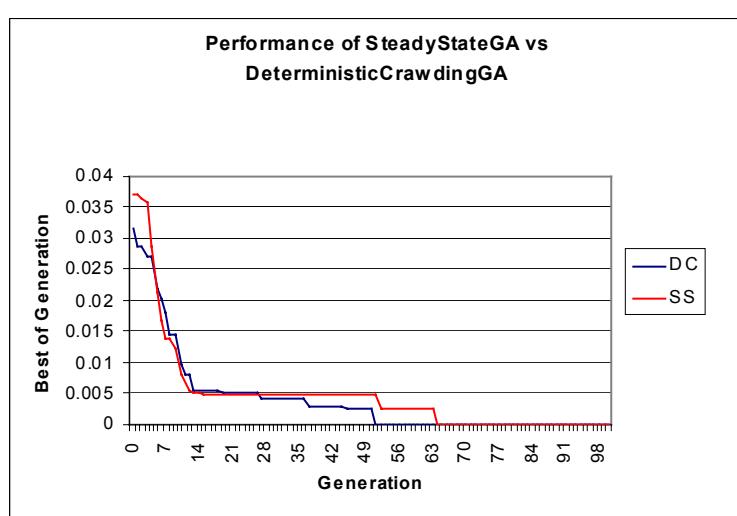


Figure 9 The performance of Steady State GA (SS) and Deterministic Crowding GA (DC)

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 desired lighting level and 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, wall, floor, and ceiling reflectance.

Figure 10 compares the average scores from 10 individual runs derived from different objective functions. The first one takes both  $f_1$  (light level) and  $f_2$  (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 typical for conflicts to occur amongst the objectives. The more objectives are considered, the more the possibility for conflicts increases, thereby increasing the difficulty in solving the problem.

Figure 11 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. However, for a higher reflectance of the lightshelf, it is not necessarily true that the lightshelf must be lowered in order to achieve the desired illuminance as shown in Figure 11. For the high

reflective lightshelf, the lower levels of the lightshelf provide too much illuminance on the work plane. For many more variables (7 variables), lightshelf depth and height, floor reflectance, and window transmittance imply significant effect on given desirable lighting conditions.

The differences between the solutions shown in Figure 11, which suggest the use of an optimization tool, may not only provide increased design quality in terms of visual perception, but also present variability 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.

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 10 Effect of the objective functions

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	0
	5	6.3	~	~	~	~	~	~	~	0	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 11 Best genomes for different variables

## Conclusions and Future Work

This paper presents a new design tool and process for daylighting design decision using a genetic algorithm. It is a generative tool to optimize daylighting design parameters by the use of the genetic algorithm (GAlib) as a search engine, and Radiance for lighting calculation, and is a visualization tool. The new objective function and design systems are created within this paper.

The method was first validated by an exhaustive test where the optimal solutions were calculated. The results from the exhaustive test were then compared with the new method. The comparison proved that the GA is the best algorithm for this set of problem. The method was then applied to a larger problem as presented earlier. The results converged to populations consisting of optimal or near-optimal solutions and the results can have some variation. 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.

This paper presented only one sample or element of the design process. However, its structure and system can be developed and applied in the future. Listed below are types of work expected to be performed in the future.

- Validate the objective function by conducting a small test or experiment with designers to retrieve real user feedback. This is an on going project.
- Speed up the program by modifying stopping criteria, reorganizing software design, and/or incorporating neural network.
- Optimize more daylight variables and constraints such as time, sky conditions, material properties, size and numbers of lightshelf, ground and facade reflectance, etc.

## References

- [1] Schoeneman, Dorsey, Smits, Arvo, & Greenberg. (1993). Painting with light. Computer Graphics Proceedings, Annual Conference Series, 143-146.
- [2] Negroponte, N. (1970). The architecture machine. Cambridge, MA: The MIT Press.
- [3] Nazzal, A., & Chatarat, A. (2000). A new daylight glare evaluation method: A comparison of the existing glare index and the proposed method and an exploration of daylighting control strategies. Illuminating Engineering Society of North America Annual Conference Proceedings. New York.
- [4] Goldberg, D., & Horn, J. (1995). Genetic algorithm difficulty and the modality of fitness landscapes. Foundations of Genetic Algorithms 3 (243-269). California: Morgan Kaufmann Publishers, Inc.
- [5] Manikas, T. (1996). Genetic algorithms vs. Simulated annealing: A comparison of approaches for solving the circuit partitioning problem. Technical Report 96-101. Department of Electrical Engineering, The University of Pittsburgh, PA.
- [6] Holland, J. (1965). Adaptation in natural and artificial systems: An introductory analysis with applications to biology, control, and artificial intelligence. Michigan: University of Michigan Press.
- [7] Jang, J. (1997). Neuro-fuzzy and soft computing: A computational approach to learning and machine intelligence. New Jersey: Prentice Hall.
- [8] Aizlewood, M. (1993). Innovative daylighting systems: An experimental evaluation. Lighting Research and Technology, 25(1), 141–152.
- [9] Littlefair, P. (1990). Innovative daylighting: Review of systems and evaluation methods. Lighting Research and Technology, 22(1), 1–17.
- [10] Littlefair, P. (1995). Light shelves: Computer assessment of daylighting performance. Lighting Research and Technology, 27(2), 71–90.
- [11] Lam, W. (1986). Sunlighting as formgiver for architecture. New York: Van Nostrand Rienhold, Inc.
- [12] Wall, M. (1999). <http://lancet.mit.edu/galib/>. Cambridge, MA: Department of Mechanical Engineering, Massachusetts Institute of Technology.