A Simulation-Based Expert System for Daylighting Design

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Abstract
In this paper, we propose an expert system for daylighting in architecture which is used to guide a goal-oriented, user-interactive design process. This system is supported by a knowledge-base which has been populated using a set of previously completed simulations using the Design of Experiments methodology. The knowledge-base contains information regarding the effects of a variety of design conditions on resultant daylighting performance. Eighty different design conditions are considered, encompassing two different values of ten design variables on four facades. Daylighting effects are considered for three times of day, for three seasons, and for five zones. The use of the knowledge-base as both a stand-alone resource and as a component of the expert system is considered. Within the expert system, the knowledge-base provides customized information based on user inputs and guides an iterative process which improves daylighting performance of the user's original design.

Keywords: Daylighting, Expert system, Knowledge-base, Design support

1. Introduction

There are many benefits to daylighting in buildings, particularly in terms of visual comfort, health and productivity, and energy consumption [1,2]. Unfortunately, successfully designing with daylighting remains a complicated task due to a high number of relevant design variables, many of which are project specific. Daylighting simulation programs have gained popularity among designers, but in general, these tools are still used more often by those with higher levels of technical expertise [3].

In this paper, we propose an intuitive goal-oriented digital expert system which can aid non-expert designers to work successfully with daylight. Expert systems, also known as knowledge-based systems, are digital tools in which domain-specific knowledge has been encoded so as to reproduce the performance of a human expert [4]. Our system will act as a digital daylighting consultant, able to evaluate a design and use a daylighting simulation tool to make design recommendations to a non-expert user. This system is part of the LightSolve approach described in [5].

The core of an expert system is the knowledge-base, a database in which the main domain-related intelligence is encoded. Such a database is typically populated using the knowledge of one or more human experts. In daylighting, such knowledge is in the form of heuristics, past experience, and ability to analyze data such as the results of a simulation or scale model study. However, heuristics and experience are only useful in very general situations, and they are not always reliable.

We propose a knowledge-base which has been populated using data from a set of completed simulations of a base case building. By using experimental data rather than heuristics to populate the knowledge base, our system can consider highly specific goals and multiple sets of goals for the same design, which can differ based on the daily time period(s), season(s), or zone(s) of interest within a space. The proposed knowledge base will also include quantitative rather than qualitative data, allowing for more logical and accurate comparisons of multiple design options.

The completed simulations were selected using a fractional factorial design of experiments approach. Variables include window size, shape, and location, number of windows, distribution of windows on the facade, shading device type (horizontal or vertical), and glazing material for windows on each of the four cardinal orientations, as well as interior reflectance. Such variables were chosen because they are typically early design decisions which may greatly affect daylighting performance. Illuminance level results were obtained for five different zone orientations (North, South, East, West, and core zone), during three different periods of day (morning, mid-day, and afternoon), and during three different seasons of year (Summer, Autumn/Spring, and Winter). The current knowledge base is a case study for Boston, MA. In future studies, additional cities will be added.

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2. Feasibility study

A feasibility study was conducted using a preliminary knowledge-base which contains information about how the illuminance levels in a test model were affected by five different variables: window size, shape, vertical location on the façade, horizontal location on the façade, and existence of a horizontal shading device. This knowledge-base was used to improve three case study buildings with increasingly complex goals. It was found that in each case study, daylighting performance was improved (approached the goal conditions) after design changes suggested by the expert system were implemented. The improvement of the case study buildings ranged from 12% to 32% after six design changes. Further details of this study can be found in [6]. Based on the success of this preliminary study, a more comprehensive knowledge-base is proposed in this paper. This knowledge-base includes information about the effects of ten design variables on illuminance.

3. Knowledge-base population

The knowledge-base developed for the expert system contains information about the relative effects of various facade and interior design conditions on the mean illuminance levels on a workplane. Such effects are available for design conditions on facades oriented towards each of the four cardinal directions, for five different zone orientations (four perimeter zones and one core zone), for three different periods of day (morning, mid-day, and afternoon), and for three different seasons of year (Summer, Autumn/Spring, and Winter).

Traditionally, the knowledge acquisition process used to populate a knowledge-base involves two people (or groups of people): an expert in the domain and a knowledge engineer. The human expert provides information to the knowledge engineer, who then encodes it as data in the knowledge-base. However, due to the dynamic nature of daylight and the large number of design variables that can affect performance, it would be difficult or impossible for a human to accurately provide the information required to populate the knowledge-base. For our system, a set of simulations has been used which allow us to obtain highly specific data. The following sections describe the methodology used to obtain this data.

3.1 Design of Experiments methodology

Because information regarding a large number of design variables was required for the knowledge-base, the Design of Experiments (DoE) method was used. Design of Experiments is a formal method of experimentation which allows the experimenter to obtain information about how independent factors (variables) affect a given output, relative to each other [7]. Two-level designs involve the study of two different values, also called levels, of each factor. Results of the DoE method include main effects, two-level interaction effects, and higher level interaction effects. The main effect of one level of a given factor is the effect of that factor's value, averaged across all values of all other factors, on the output. Interaction effects indicate how the output is affected by specific combinations of two or more factor values, averaged across all combinations of all values of other factors. A positive effect indicates that the output is, on average, increased when the factor (or set of factors) is at the specific level(s) tested, while a negative effect indicates that the output is, on average, reduced by the tested value or group of values.

Before calculating the various effects, one must first run a set of experiments. These experiment sets may be "full factorial", which include all combinations of factors and levels, or they may be "fractional factorial", which include a smaller number of experiments based on an orthogonal matrix of level combinations. The feasibility study [6] considered only five factors, so a full factorial set of experiments was possible. For the present study, the number of factors is increased to ten, so a fractional factorial design is used to reduce the number of necessary experiments per façade. The resolution of a DoE scheme refers to the quality of information obtained by the set of experiments, specifically the amount of possible confounding with higher order interaction effects. For example, the main effects of a Resolution III or Resolution IV design may be confounded with two-level or three-level interaction effects, respectively, and all higher-order interaction effects will also be confounded. A Resolution V design results in non-confounded main effects and two-level interaction effects.

For this study, we used a two-level fractional factorial Resolution V design. 128 simulations were performed for design variables on each façade orientation examined (four in total, corresponding to the cardinal directions). At present, the knowledge-base includes the main effects obtained from these experiments; however, two-level interaction effects may be included in a future iteration.

3.2 Simulation models

A generic base case model was used to run the simulation-based experiments. The test model is a single height space which is 30ft by 30ft in area and 10ft in height (9.1m x 9.1m x 3.1m). The four facades are oriented towards the four cardinal directions. Interior materials are entirely diffuse. Illuminance is measured on a sensor plane located at a workplane height of 3ft (0.9m) above the floor. The sensor plane is divided into five zones, one for each perimeter zone and a core zone which is 10ft by 10ft (3.1m x 3.1x) in area (Figure 1).

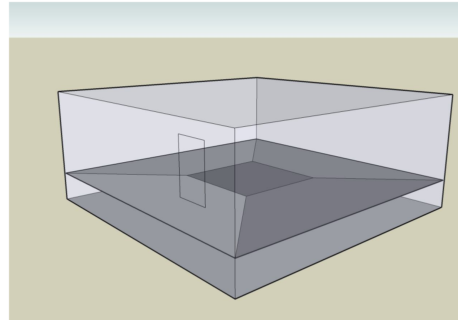

Figure 1. Test model with five sensor plane zones indicated in different shades

The test model was designed based on the well-known window-head-height heuristic: light from a window may penetrate into the space a distance that is up to 1.5 times the window head height for windows with shading devices and up to 2.5 times the window head height for unshaded windows [8]. The zone boundaries occur at depths of 1, 2, and 3 times the window head height for windows located at the maximum height, which roughly correspond to a daylit zone, a drop-off zone, and a deep zone. The differentiation between the effect of a design change on different zones in the room allows the knowledge-base to be more customizeable than if information was only obtained in one zone.

A separate model was created for each experiment trial (128 in total for each façade). These models had the same overall form and a single exterior façade through which daylight could enter the space. The façade design (windows and shading devices) and the interior reflectances were varied in each model.

3.3 Design factors

The design factors examined in this study included window geometry, location, and distribution on the facade, shading device geometry, and material properties. Window variables consisted of: total window area, window shape (narrow or wide), vertical location of windows on the façade, horizontal location on the façade, number of windows, and window distribution on the façade. The number of windows variable did not affect the total area; for the larger number of windows, each individual window area was decreased so that the total area remained the same. The window distribution variable referred to the distance between each window. Shading device variables consisted of: existence of a horizontal overhang and existence of vertical fins. The horizontal overhangs were dimensioned to block direct sunlight on the equinox at noon in Boston, MA. The vertical fins had the same length as the overhangs. Material variables consisted of: glazing transmissivity and interior reflectances of walls, ceiling, and floor. The glazing transmissivities corresponded to clear glass and tinted glass. The interior reflectances corresponded to near-white surfaces and to medium gray surfaces. The values examined for each design factor are indicated in Table 1.

Table 1. Values tested for each design factor

	Levels	
Parameter	**1**	**2**
Window Area	10% of wall area	20% of wall area
Number of Windows	Two	Three
Window Shape	1:1.5 height-to-width ratio	1.5:1 height-to-width ratio
Vertical Location of Center Pt.	3.5ft (1.1m) from floor	6.5ft (2.0m) from floor
Horizontal Location of Center Pt.	10ft (1.5m) from left edge of wall	20ft (1.5m) from right edge of wall
Window Distribution	Close Together	Far Apart
Horizontal Overhang	None	Overhang
Vertical Fins	None	Two Fins
Reflectances (Ceiling / Wall / Floor)	60% / 50% / 20%	80% / 70% / 40%
Glass Transmissivity	85% (Clear)	50% (Tinted)

An example simulation model can also be seen in Figure 2. For this model, the south façade is examined. The design factor values are: small window area, three windows, wide windows, high vertical location, left (west) horizontal location, close distribution, horizontal overhang, vertical fins, light interior reflectances, and clear windows.

3.4 Simulation Engine and Output

The simulation engine used in this study, the Lightsolve Viewer (LSV), is an efficient hybrid global rendering method which combines forward ray tracing with radiosity and shadow volumes rendering. This algorithm is described in [9]. The engine creates rendered images of daylit scenes and calculates the illuminance on area-based patch sensors. Early validation results indicated that rendered images by LSV displayed a pixel difference of less than 10% from Radiance for a variety of scenes, camera positions, and daylighting conditions [9]. Analysis comparing data collected from area-based patch sensors with point sensors in Radiance indicated similar values with an overall highest difference of 28% [6]. Further improvement and validation of this engine is currently underway.

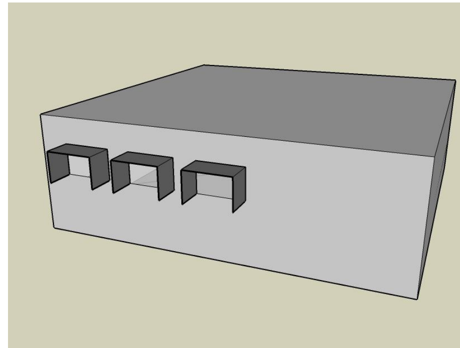

Figure 2. An example simulation model with South-facing windows

For each model in the Design of Experiments scheme, the LSV engine is used to calculate the mean climate-based illuminance due to daylight on the five sensor plane zones (four perimeter and core) over the whole year. For each time period considered, illuminance is calculated for four different sky types, ranging from overcast to clear. The climate-based illuminance is then calculated as a weighted average of illuminances from each sky type. To make the whole-year simulation more efficient, the year is divided into 56 periods. These climate-based and temporal simplification are validated in [10]. Results from the 56 periods are then averaged into a total of nine general time periods: morning, mid-day, and afternoon for Winter, Autumn/Spring, and Summer. The final result of each simulation used in the DoE scheme is a set of 45 mean illuminances, corresponding to five sensor zones, three periods of day, and three seasons. These illuminance values are then used to calculate the main effects for each design variable over each zone, time, and season.

4. Knowledge-Base Results

The knowledge-base is a 45x80 matrix containing the main effects for eighty design conditions total (two different values of ten variables on each of four facades) on the mean illuminance specific to three seasons, three periods of day, and five zones. This data is specific to the location and climate for which the DoE models were simulated. For this study, the knowledge-base is specific to Boston, MA. To interpret the meaning of the main effects, one must consider both the magnitude and sign of each effect. Highly positive main effects indicate that the corresponding design condition will result in a higher mean illuminance on the relevant work plane relative to other design conditions, while highly negative values indicate that the corresponding design condition will result in a lower mean illuminance on the work plane relative to other design conditions. When comparing two main effects of the same sign, the design change with the higher magnitude is more likely to result in a higher mean illuminance if both are positive or a lower mean illuminance if both are negative.

It is important to note that main effects are calculated over all combinations of design variables in the DoE set. This is powerful because one can apply the information within it to a wide variety of designs. There may be individual cases where a design condition will not affect performance in the predicted way; however, the information contained in the knowledge-base should be considered similarly to heuristics: while not perfectly accurate in all cases, such tools are useful because they are reliable for most situations and are quick to use. Another feature of the knowledge-base is that it was designed to be customizable to specific design situations. There are a total of 1519 different permutations possible for specific combinations of season(s), time period(s) of day, and zone(s).

While the knowledge-base was created for use within the expert system framework, it is also a valuable stand-alone resource. The main effects contained in the knowledge-base can be used in a variety of ways to provide a designer with information regarding design conditions alone or relative to each other based on different combinations of zones, seasons, time periods, and facades. The following sections provide examples of ways in which one can use the knowledge-base to aid in the design process.

4.1 Ranked effects of all design actions on a specific zone(s)

A common design scenario is one in which a designer wishes to improve performance in a given zone at certain periods of time. For this situation, one can use the knowledge-base by sorting the effect of each variable on illuminance in that specific set of zones and periods of time. If one wishes to increase illuminance, one should rank by highest main effect to lowest. Those variables with the highest main effects correspond to those design conditions most likely to increase illuminance. For example, one might desire to increase illuminance in the core zone during Autumn, Winter, and Spring, at all times of day. The first 20 design conditions in the ranked set and their main effect values are indicated in Figure 3. In this chart, design conditions on all façade orientations are considered. The first letter indicates the façade on which the design change is made; for example, S_HighWindows refers to windows located towards the top of the façade on the south. A designer could also customize such a list to include only the facades on which he can make changes and to exclude non-relevant design conditions. Using such a list, a designer can easily see which design changes he might consider to improve performance. These lists are also useful teaching tools for students, who can use such information to develop better intuition about what design conditions to consider based on different scenarios.

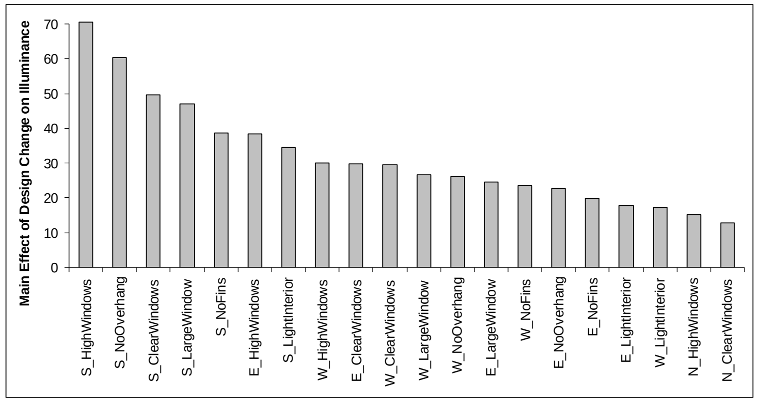

Figure 3. Main effects for all design conditions, ranked in order of likeliness to increase illuminance in the core zone over all times in Winter, Spring, and Fall

4.2 Effect of a single design action

Another scenario in which the knowledge-base is useful is the consideration of the effect of a single design change on the different zones within a space and the examination of how the effect of that design change may differ on different facades. This situation could occur if a designer wishes to adopt a particular aesthetic. For example, one might consider the effect of using wide windows. These effects, averaged over a full-year, are indicated in Figure 4. One can see from this chart that the different zones are affected to various degrees by the same design change. This information is valuable because it clearly indicates the relative effects of the design change over all possible scenarios.

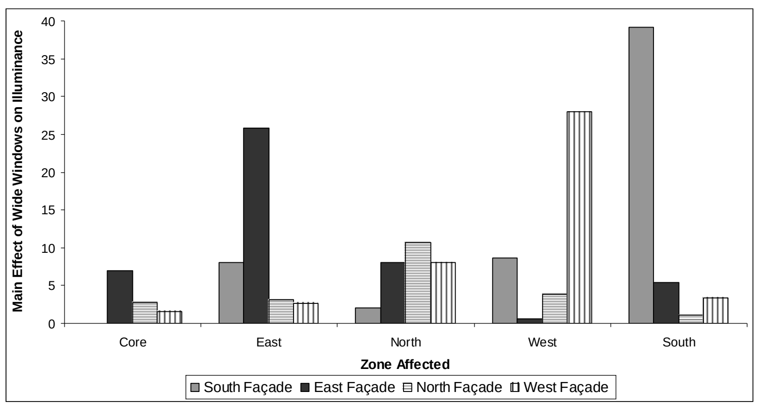

Figure 4. Main effects for wide windows on all four facades, averaged over the whole year, for all five zones

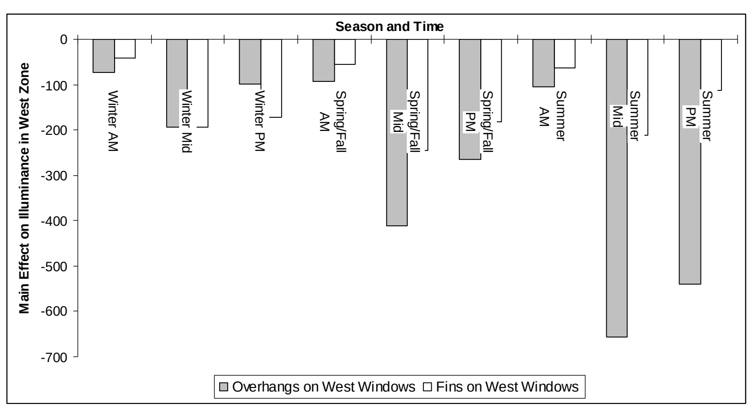

Figure 5. Main effects for West-facing overhangs and fins on the West zone for all time periods

4.3 Effect of design actions over all periods of time

A final example of when the knowledge-base could aid in design decisions is when a designer is considering the effect of a design change over different periods of time of day and year. This type of information allows a designer to consider full-year effects for a particular change in a simple and clear way. For example, a designer may wish to consider the effect of an overhang versus that of fins on West façade windows over the course of a year. The main effects for these two shading devices on the illuminance levels in the West perimeter zone (closest to the windows) are indicated in Figure 5. It is clear from this chart that the two types of shading devices perform differently relative to each other in different seasons. Such information is important when considering whole-year performance yet may not always be intuitive. Using such a chart, one can quickly consider the benefits of using one type of shading device over another depending on occupation schedule or other design parameters.

5. Expert System

In addition to being an informative stand-alone resource, the knowledge-base is a critical component in the expert system. The goal of the proposed expert system is to emulate a human daylighting consultant, capable of evaluating an initial design and set of performance goals and suggesting design changes which may improve performance. The system guides the user through a step-by-step process in which the performance gradually progresses towards the user's goals while maintaining the integrity of the original design. This system is meant to be user-interactive, flexible, and compatible with most traditional building footprints and dimensions. The following sections describe the major elements in the expert system.

5.1 User input

Initial user input includes information about the design geometry, materials, and performance goals. Geometry information is currently given as a 3D model, created in Google SketchUp. Material properties including glass transmissivity and interior reflectances must also be specified. Performance goal information includes illuminance ranges, one or more goal sensor planes, and the time period(s) and season(s) during which the performance goal(s) should be achieved. Illuminance ranges can consist of a minimum and/or maximum illuminance. Sensor planes are modelled as horizontal 2D planes within the 3D model. Goal time periods can include any combination of morning, mid-day, and afternoon for Winter, Spring/Autumn, and Summer.

In addition to initial inputs, users must provide constraints on any design changes suggested by the expert system. These inputs occur during the expert system design process and are specific to the design change suggested. For example, the expert system may suggest that overhangs be added to the South facing windows, and the user must provide the system with the maximum depth that the user will allow for such overhangs.

5.2 Goal-based metric

In order for the system to work towards user-based performance goals, a goal-based illuminance metric was used. This metric is defined as the percentage of time (during the goal time period(s)) and of total sensor plane area in which the illuminance falls within a user-defined goal illuminance range. The expert system will attempt to increase the value of this metric through each suggested design change. A value of 100% indicates that the climate-based illuminance calculated for the given design is within the goal range for the entire sensor plane area over the entire year (or over the entire set of goal periods of time). This metric is a numerical version of the graphical metric presented in [10] and uses the same logic for climate and temporal simplifications. The LSV engine is used to efficiently calculate this metric within the expert system process.

5.3 Customized knowledge-base

While the knowledge-base contains a large amount of useful information, much of it may not be applicable to a user's given specific design and set of goals. Within the expert system framework, a customized knowledge-base is created each time a user initiates a new project. This customized database is produced using relevant information about the user's design such as the user's specific goal time periods and applicable zones within the user's original model. Applicable zones are determined based on the position of the goal sensor planes within the input model geometry: a sensor plane located within a distance of 1 time the ceiling height is considered peripheral to the closest wall; a sensor plane between 1 and 2 times the ceiling height from a given wall is considered a core zone; and a sensor plane located deeper than 2 times the ceiling height from a wall is considered a deep zone. For sensor planes which encompass multiple zones, the average value of relevant zone effects is calculated.

If the user specifies multiple sensor planes within the input model, multiple customized knowledge-bases are created, and more intelligence is necessary for the expert system to perform. Orthogonal projections of each sensor plane are used to divide the facades into discrete sections, and the relevant zones for each customized knowledge-base are determined based on the sensor location relative to these wall sections. These wall sections are also ranked in terms of likelihood to affect each sensor plane, where such ranking is based on the sensor's distance and angle from each wall section. For example, Figure 6 shows a model where the orthogonal projections of two sensor planes divide the south and west facades into four total sections. In this example, the W1 wall section would be ranked highest for in likelihood to affect sensor 1 and lowest for sensor 2.

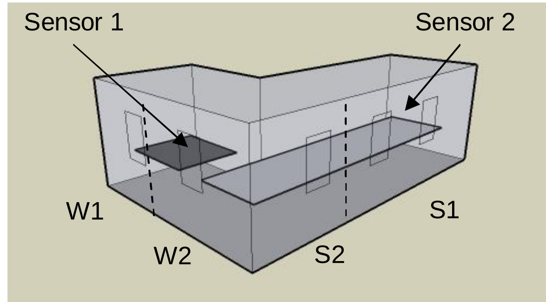

Figure 6. Example model with two sensor planes

5.4 Determining a design change

At each step in the guided design process, the expert system must select a design change to propose to the user in order to further improve performance. To do so, the system must first determine how the daylighting conditions in the current model must change in order to move closer to the user's goals. The LSV engine is used to calculate the percentage of area and time that each sensor plane is within the goal range, as well as the percentages above and below the goal range. In situations in which only one sensor plane is used, the customized knowledge-base will recommend a design change based on which value, the percentage higher or lower from the goal range, is greater. For example, if a given sensor plane is 60% within the goal range, with 10% high and 30% low, the expert system will attempt to increase illuminance over the sensor plane.

In situations in which multiple sensor planes are used, the expert system will negotiate between multiple customized knowledge-bases. The strategy used in this situation is to select the design change most likely to improve the worse performing sensor plane. For example, if sensor plane 1 is 50% within the goal range and sensor plane 2 is 70% within the goal range, the expert system will attempt to improve sensor plane 1 as if only sensor plane 1 existed. This generally means that after a few iterations, the façade sections with the highest influence on the worse performing sensor planes will be changed the most. This strategy also tends to equalize performance over all sensor planes after a few design changes. If two sensor planes perform within 5% of each other, the expert system will compare the two corresponding knowledge-bases and choose the design change most likely to improve both sensor planes simultaneously.

5.5 Determining the magnitude of a design change

If a suggested design change is approved by the user, the user must specify how large a change he will allow. The expert system will then determine the optimal magnitude of the change. The system uses a sampling method, testing four models corresponding to the original (no change), maximum change (based on user input), and two models with design changes equidistant from the two extremes. The performance of each sample model is determined and compared. The design with the highest performance is accepted, and the model corresponding to this design is used in the next iteration. For example, if the system suggests translating the south windows towards east, and the user indicates that he will allow a maximum translation of 4.5 ft, the system will then create and simulate models where the south windows have been translated 0, 1.5, 3, and 4.5 ft. Figure 7 indicates the percentage in the goal range for these four sample models, and the model corresponding to a translation of 3 ft has the highest performance. For situations with multiple sensor planes, the performance is averaged at each point.

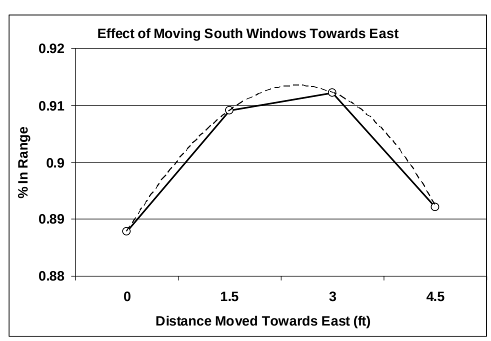

Figure 7. Performance for four sample models with increasing translation of south windows

5.6 Process and Stopping Criteria

The expert system guided design process consists of an initial user input and a series of interactive design steps. At each step, a single design element is changed and the performance of the design should improve or stay the same. The user may elect to skip the suggested design change at any iteration, which prompts the system to suggest an alternative design change. The process will end when one of the following criteria are met: 1. the user elects to stop the process; 2. the performance goals are entirely met (all sensor planes are 100% within goal range for all desired times); 3. the expert system iterates through all possible design changes and no further improvement is found.

6. Conclusions

A daylighting expert system has potential to act as a virtual daylighting consultant and to guide designers towards improved designs during the schematic design phase. A preliminary study has shown to improve designs for a variety of goal complexities. The present paper proposes a more comprehensive knowledge-base with an expanded set of design variables. This knowledge-base is valuable both within the expert system framework and as a stand-alone resource. As a stand-alone, the knowledge-base can provide information for a variety of situations which can be used directly to inform a designer during the design process. Within the expert system, the knowledge-base provides the necessary intelligence to guide the user towards design decisions which will approach the user-defined performance goals within specific user-defined design constraints.

Both the knowledge-base and the expert system have educational value in that they provide users with information to help them improve their design performance, and students or new designers who use these tools repeatedly may gain intuition about the effects of certain design conditions on daylighting performance. Because the information obtained in the knowledge-base is applicable across most situations, such intuition may also be gained more quickly than through normal design experiences, where only highly specific situations are considered at a given time. These methods may also aid in design exploration in the professional design context. The knowledge-base allows the designer to efficiently compare different design conditions in a clear manner while the expert system allows for intelligent search of design changes while respecting the user's original design. The use of these tools during an actual design process will be the subject of a future study.

Additional future work will involve the expansion of the knowledge-base to include daylighting performance metrics such as illuminance on vertical planes, glare, or solar thermal gains. The addition of such metrics will allow users to obtain more complete information about daylighting performance and will aid in the design of more comfortable environments. The addition of these new metrics will necessitate further investigation of search or optimization methods for use within the expert system, particularly since illuminance and glare goals may conflict. Validation of the method over a variety of geometrical cases and against traditional optimization methods will also be completed.

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