DECISION-MAKING FRAMEWORK FOR SELECTION AND DESIGN OF SHADING DEVICES BASED ON DAYLIGHTING

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ABSTRACT

This research looked to improve the daylighting performance of a shading device as a window component. The paper describes the development of the decision-making framework (DMF) for the selection and design of shading devices based on daylighting. The DMF presents the process of analysis of the shading devices' daylighting performance in the selection of existing shading devices and in the design of new shading devices. The research determined the shading device daylighting performance measures (such as illuminance and daylight autonomy) as well as the variables that influence daylight performance. Interactions among the variables and the effects of these interactions on the shading device daylighting performance were explained and quantified in the DMF. The DMF also included ways of presenting the results of testing the shading devices and the process of making the decision.

A case study for three blind systems was performed to determine if the DMF provides a concept for the analysis of the daylighting performance of shading devices and for making decisions about the design/selection of the shading device. Computer simulation was used to calculate the illuminance levels and the daylight autonomies (DAs) as a result of the application of these blinds. The values of the DAs are compared for three blind systems to select the most appropriate system to be applied on a proposed building.

The DMF based on daylighting can help building designers to select the most suitable shading device based on its daylighting performance, and can help shading device manufacturers in designing new shading devices with improved daylighting performance.

KEYWORDS

decision-making framework, shading device, daylighting, transparent blinds, illuminance, daylight autonomy, and simulation

1. INTRODUCTION

A shading device is an important component of any façade system. A shading device regulates heat by maximizing reception of welcome heat in winter, and excluding the excessive heat penetration in summer (Olgay and Olgay 1957). By providing protection from direct sun and overheating, shading devices reduce cooling loads for buildings in the summer. Therefore, direct sun radiation through the window should be prevented by the appropriate application of shading devices (Schuman et al. 1992). A shading device is also used for providing glare protection and privacy. Proper application of the shading device is especially important in curtain wall systems. Large glass areas can create a green house effect. Glass can also cause visual problems with direct and reflected glare (Dubois 2001). Therefore, the application of shading devices in windows and large glass façades is necessary for controlling sunlight penetration through the glass.

A shading device used as a daylighting system can redirect daylight to spaces where daylight is needed, for example, to spaces at a large distance from the window wall. Use of daylight decreases the use of artificial lighting which causes a decrease in the use of electricity, a decrease in internal heat gain from lighting, and thus a decrease in the cooling load. This

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leads to energy savings for the building. The application of daylighting can decrease energy costs by 30% (Ruck et al. 2000). However, the use of shading devices in windows can also obstruct the view to the outside and limit the amount of the daylight that penetrates into the interior space.

The shading device, as part of the fenestration system, is also an important architectural element. The window as a transparent façade element transmits, reflects, or absorbs sunlight, and the shading device as the window component should help in these processes. The type and position of the shading device system should be selected by the building designer based not only on experience but also on a performance evaluation of such a system. Currently designers have very few means of systematically selecting/designing shading devices for buildings, be they external systems or internal systems. The lack of a robust method for the shading device selection/design can lead to improper application and performance of shading devices in buildings. As a result, the energy-efficiency of the building is decreased, occupants' comfort may not be achieved, and a sustainable building design is not accomplished.

This research developed a decision-making framework (DMF) for the selection and design of shading devices based on daylighting. The DMF can be used for an analysis of the daylighting performance of shading devices in order to select the best possible system from several alternatives. The user of the DMF can be either the building designer or the manufacturer of a shading device system. The building designer can use the DMF as an analysis tool in the process of the selection of available shading device systems. The manufacturer can use the DMF in the process of designing a new shading device system.

1.1. Literature Review

Selection/design of a shading device in the proposed DMF is based on the analysis of the performance of the shading device. Therefore, the main criteria in this DMF are performance criteria, with a focus on the daylighting performance of shading devices. A literature review on the performance of shading devices was conducted to obtain the results from previous research on the thermal and daylighting performance of shading devices as well as the calculation methodologies for the performance parameters. These results and methodologies were the basis for the development of the methodology for testing the daylighting performance of shading devices in this DMF.

The proper design of a building, with a window as a building component, has as a goal providing comfort for the occupants and energy-efficiency for the building. The use of daylighting helps in achieving these goals. The use of artificial lighting in a building causes considerably higher costs than the heating and cooling of the building (Koster 2004). The appropriate use of a shading device in a window also contributes to energy savings. Well designed shading devices help in increasing the daylight levels in the space and in protection from overheating. When designing a window and a shading device for the window, the goal is to achieve a low, total energy transmittance (g-value) while maintaining high light transmission and good transparency (Koster 2004).

Shading devices currently available on the market are either static (fixed) or dynamic (moveable). Previous research on the advantages of the application of a dynamic Venetian blind compared to a fixed blind showed that a dynamic system always blocks direct sun, provides a view when there is no direct sun (a maximum view was possible for at least 50% of the day throughout the year), and provides a controlled illuminance level throughout the day (Lee et al. 1998). The use of static blind systems requires higher energy consumption for lighting compared to dynamic blind systems (Galasiu 2004). Dynamic Venetian blinds contribute to cooling load reductions and daily lighting energy savings, especially if dimmable daylighting controls are used although most state energy codes require a minimum stepped, dual level manual switching (Lee et al. 1998).

The position of dynamic shading devices can be adjusted either manually or automatically. For manual operation with fully retracted blinds, lighting savings would be decreased, and cooling loads would increase (Lee et al. 1998). Motorized Venetian blinds can maintain workplane illuminance of 538 lux if there is sufficient daylight. If there is no sufficient daylight, continuous electric lighting can add supplementary lighting to maintain a design illuminance level in the space. As a result of this strategy, electric lighting and cooling energy savings were found to be significant

(DiBartolomeo et al. 1998). The thermal performance of an automated blinds system is much superior (lower by 68.83–88.75%) to the performance of an ordinary window system without blinds when cooling is needed. The use of automated Venetian blinds decreases the cost of energy by 30% during the winter and by 50% during the summer (Bilgen 1994).

Shading device control systems should be designed properly in order to provide a sufficient amount of daylight in the space and protection from overheating. The use of daylight responsive controls provides adequate quantity and quality of daylight in interior spaces, saves energy, and improves the overall distribution of light when daylight is insufficient. It is possible to conserve cooling energy by increasing the use of daylighting and also using daylighting-responsive lighting controls, provided that solar heat gain is also controlled (Ruck et al. 2000). The proper use of blinds provides lighting energy savings in comparison to cases in which blinds are fully retracted, and electric lighting is fully on (Galasiu 2004).

A shading device can be installed outside, in front of the facade, inside the facade, in the interior space, between two panes of glass in the double insulated glass unit, or in the cavity between two facade layers in the double-skin facade. A comparison between the between-pane and the external dynamic blinds shows that approximately the same lighting energy savings can be accomplished by applications of both systems (Lee et al. 1998).

The daylighting performance of Venetian blinds depends on the sun's angle of incidence, on the slats' shape and on the tilt angle of the slats. If the slats are rotated, and light is transmitted only by multiple reflections, the shape of the slats will affect the light distribution in the space. Curved horizontal slats will transmit light in an upward direction while flat slats will transmit light in a forward direction. Breitenbach et al. (2001) developed a daylighting simulation model that can predict performance at the normal angle of incidence. The model is useful for investigating the effect of changing the properties of individual components of the system without the need for experimental testing of all possible combinations.

Scuito (1998) conducted research on an integrated approach to Solar Control Techniques in order to investigate the performance of the shading device systems. The use of the shading devices to control solar radiation and visible radiation was the solar control technique investigated in this research. The final products of this research were: a proposal on testing standards for shading devices, an upgrade of the existing simulation models, a design of a smart solar control assembly, a set of design guidelines, and a shading component handbook (Scuito 1998).

1.2. Problem Statement

Based on the literature review and current state of the art in this research area, the following problems related to a shading device's application and performance as well as to the method for shading device selection and design have been identified:

- There is a lack of specific guidance for the analysis of shading device performance in the process of the selection of available shading devices and the design of the new shading devices.
- Shading devices are not often used as daylighting systems, solar collectors, or thermal barriers. Existing shading devices currently available in the market have limited application: to protect from overheating in summer, to protect from glare, and to provide privacy.
- Static (fixed) blinds have inferior performance compared to dynamic (moveable) blinds.
- Manually controlled blinds often do not meet thermal and visual performance requirements.
- There is a lack of appropriate control systems used to adjust the blinds' tilt angle. A balance between a sufficient amount of daylight and maximum overheating protection can hardly be achieved without the application of automatic control systems.
- Interior shading devices have inferior performance compared to the between-pane shading devices.
- The shading device slats are usually made of non-transparent materials. If the blinds are in a closed or partially closed/open position, the direct view to the outside is obstructed, and transparency of the façade is not achieved.

2. RESEARCH OBJECTIVES AND METHODOLOGY

The goal of this research was to study and to try to improve the daylighting performance of shading devices by developing a DMF for the selection and design of shading devices based on daylighting. The objectives of the research were to:

1. Determine the variables that affect the daylighting performance of shading devices.

   To accomplish this objective, the following tasks were performed: Variables that affect daylighting performance of shading devices were categorized, major variables as well as subvariables for each category of variables were determined, and relationships and interactions among these variables were defined.
2. Determine the daylighting performance parameters, such as illuminance and daylight autonomy.

   To accomplish this objective, the following tasks were performed: The two daylighting performance parameters, illuminance and daylight autonomy, were defined and explained; and interactions and relationships among the variables and daylighting performance parameters were determined.
3. Identify the measures for the variables and daylighting performance parameters and sources of measures.

   To accomplish this objective, the following tasks were performed: Measures, that is, values and units, and sources of measures for each variable and the two daylighting performance parameters were identified.
4. Develop the DMF based on daylighting.

   To accomplish this objective, the following tasks were performed:
   - The decision problem was defined.
   - The influence diagram and the decision-making tree/chart were developed.
   - The input and output parameters in the DMF and the relationships among them were defined.
   - The process of making a decision based on the output data was described.
5. Test the DMF based on daylighting to find out if it works and if it provides a concept for both the analysis of the daylighting performance of shading devices and for making the decision about the design/selection of the best possible shading device.

   To accomplish this objective, the following task was performed: A case study for the different shading device systems was conducted to illustrate the DMF based on daylighting. The model was run for a particular building type and building location and for :
   - An existing shading device currently available on the market (System A).
   - A patented shading device (System B).
   - A new undeveloped shading device proposed by this research (System C).

3. LIMITATIONS OF RESEARCH

In this DMF, the research focused only on the daylighting performance of shading devices and only on illuminance and daylight autonomy. The research was conducted only for:

- An office building that contains computers
- One type of shading device: Horizontal Venetian blinds, installed either in the interior or between two panes of glass
- One location: Roanoke, Virginia, USA
- Climate conditions on March 21, June 21, and December 21
- Two façade orientations: south and west
- Three times of day—11:00 a.m., 12:00 p.m., and 3:00 p.m. for south orientation, and 12:00 p.m., 2:00 p.m., and 4:00 p.m. for west orientation

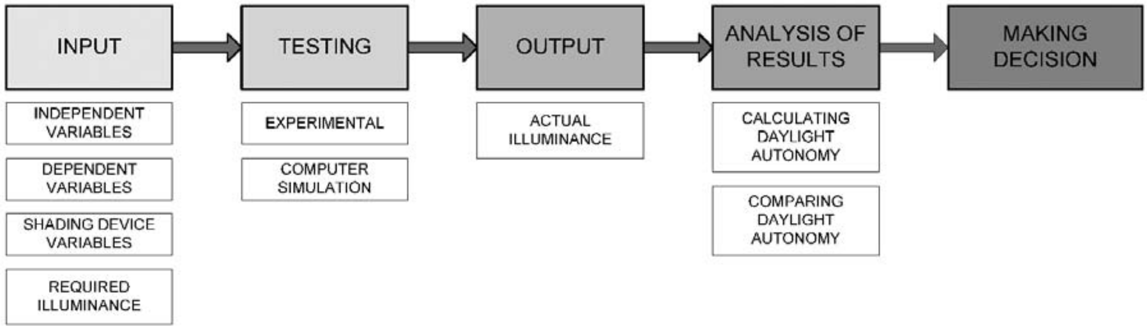
In this research, only theoretical testing of the DMF based on daylighting was conducted. The Autodesk VIZ 4 software was used to calculate illuminance in the space as a result of the application of three different blind systems.

4. DECISION-MAKING FRAMEWORK (DMF) BASED ON DAYLIGHTING

4.1. Decision-making Process Steps

The user of the decision-making framework (DMF) needs to understand not only the structure of the DMF, but also how to use the input and output information of the DMF to make the decision about the selection/design of a shading device (Clemen 1996). The objective in this decision situation is to select the best possible shading device among various shading devices. In the decision-making process for the analysis of a shading device's daylighting performance, the user of the DMF goes through the following five steps (Fig. 1):

FIGURE 1. The decision-making process steps in the DMF based on daylighting.



- *Identifying the input parameters*: The user of the DMF identifies independent, dependent, and shading device variables, as well as the range of values of the required illuminance. These input parameters are assigned particular quantitative or qualitative values.
- *Testing the shading device's daylighting performanc*e: The input is used for testing that can be performed either experimentally or with simulation software. Testing is repeated for different days during the year, different times for each of those days, and therefore, for various sun angles, outdoor illuminance, and sky conditions. Testing is repeated individually for each type of shading device. If the blinds are adjustable, then the shading device is tested for various blind tilt angles, from completely open to partially open/partially closed, and finally to completely closed.
- *Obtaining output results*: The output of both experimental and computer testing is the actual value of the illuminance level in the space as a result of the application of the specific shading device in the building. The output information is gathered, organized, and prepared for analysis.
- *Analyzing results*: The analysis of the results includes calculating daylight autonomies (DAs) and comparing the values of DAs for various types of shading devices.
- *Making the decision*: Based on the analysis of the results—comparing the DAs— the shading device that has the highest values of DA is selected as the preferred shading device for the particular building.

4.2. Structure of the Decision-making Framework (DMF)

4.2.1. General DMF. First, a general DMF that includes possible variables and performance requirements and defines relationships and interactions among them in general rather than a detail level was created. A simplified diagram of the general DMF is shown in Figure 2. By expanding the simplified diagram and adding more details, that is, defining subcategories for each major variable and performance requirement, a general and more complex DMF for the shading device selection and design was developed.

The general DMF is shown in Figure 3. Independent variables are given to the designer, and they cannot be changed. Dependent variables are defined by the designer of the building, façade, and shading device system. Shading device variables can be either independent or dependent. Shading device variables are independent in the process of the selection of the existing shading device because the building designer cannot change variables that are already defined by the manufacturer. Shading device variables are dependent in the process of the design of the new shading device because the designer of the shading device decides the values of the shading device variables. Performance parameters considered in the general DMF are thermal, visual, acoustic, aesthetic, control, and cost, including possible subparameters for each performance parameter.

The general DMF can be divided into several specific DMFs that analyze various performances of the shading device. The general DMF shows the complexity of the problem and needs to focus research on only

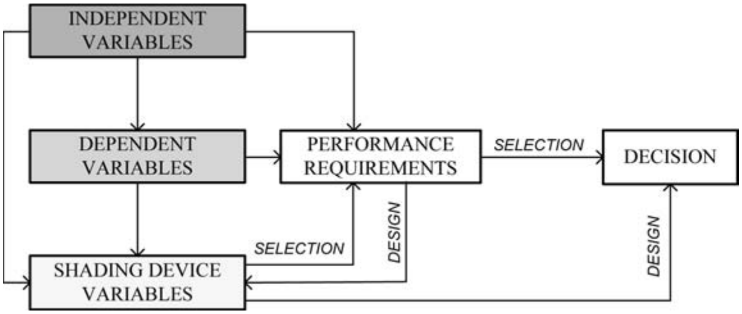


FIGURE 2. Simplified DMF diagram.

one performance parameter and investigate in detail possible factors that affect this particular performance parameter. Visual performance of the shading device is highlighted in Figure 3 to show that this research focuses particularly on daylighting illuminance and daylight autonomy as performance parameters relevant in the selection/design of the shading device.

Development of the specific DMFs for the rest of the performance parameters for shading devices introduced in the general DMF, such as thermal, acoustic, aesthetic, cost, and control systems, and the remaining visual performance parameters is the objective of future research.

4.2.2. Specific DMF Based on Daylighting. The decision-making framework (DMF) based on the daylighting performance of shading devices is a main result of this research (Fig. 4). The DMF based on daylighting provides the concept for an analysis of shading device's daylighting performance. The structure of the DMF based on daylighting was created by identifying variables and performance parameters, as well as relationships and interactions between them. The design of the structure of the DMF is crucial because it helps the user of the DMF understand which variables to analyze in the process of designing the building and in the process of the selection/design of a shading device. In this DMF, variables are organized in three categories:

1. Independent: The independent variables impact the values of the dependent variables and shading device variables. Independent variables include: climate, site, and building type. Climate is determined by the building location. The DMF includes the following climate variables: outdoor illuminance; sky conditions; and sun angle. The sources of the measures for the climate variables can be: experimental measurements for the particular site; statistical climate data from the particular weather station; or mathematical calculations. The building site directly influences the microclimate and daylighting performance of the shading device. The following site variables are considered in the DMF: the existing site; the surrounding buildings; the influence of the site on the façade orientation; the characteristics of the local terrain; the vegetation; and self-shading. Sources of measures are databases developed for each site variable.

The building type directly affects the dependent variables such as the façade type and the shading device variables. The building type also influences the following variables: the fenestration dimension and position in the wall; the reflectance of the interior surfaces; the room dimensions; and the height of the working plane as well as the type of the tasks performed in the building. Based on the types of tasks, the required daylight performance of the shading device can be determined by active standards, codes, and recommendations. The source of measure for the building type is a database of the various possible building types. This database is linked to a database of possible tasks that can be performed in the particular space.

2. Dependent: variables that depend on the values of the independent variables. The dependent variables include: the façade type and the position of the shading device in the façade. In this DMF, the façade type includes the various window types in a conventional wall or in a curtain wall. The choice of the façade type depends on the climate, site, and building type. The application of the specific shading device in the window depends on the façade geometry and the applied façade materials. The sources of measures for the façade types are databases of various

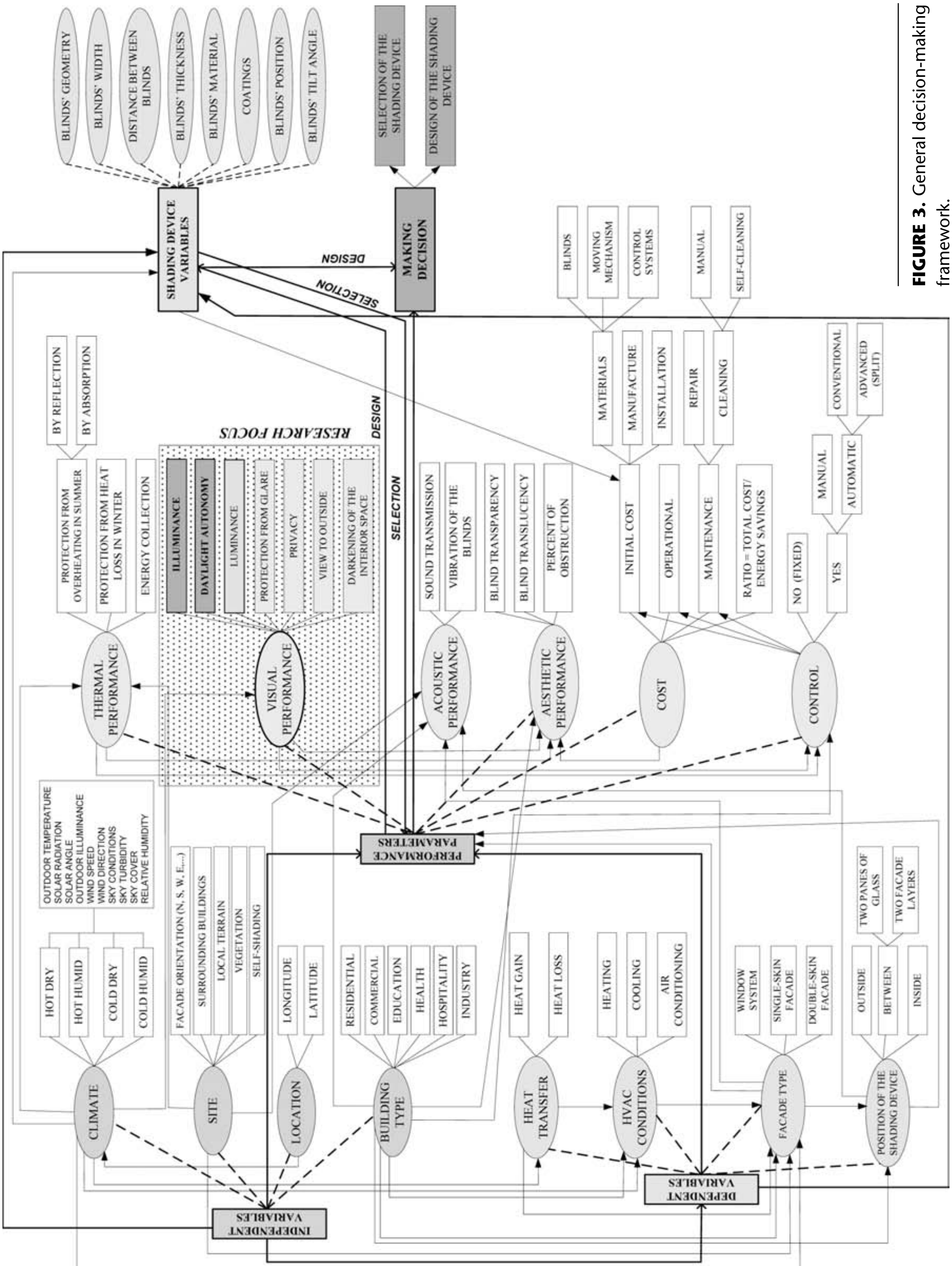


FIGURE 3. General decision-making framework.

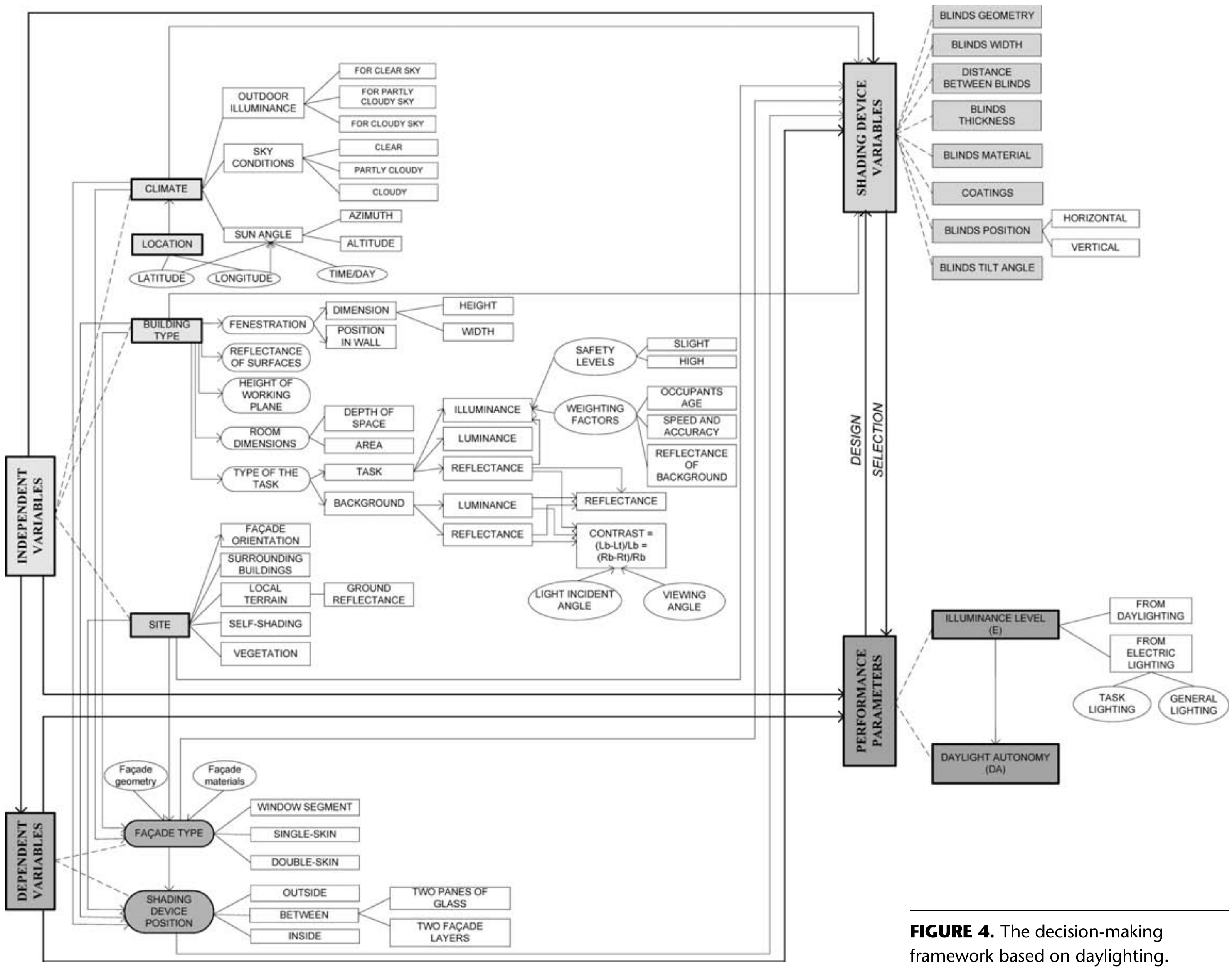


FIGURE 4. The decision-making framework based on daylighting.

types of façades/windows depending on their structure, applied materials, and geometry. The position of the shading device in the façade depends on climate, site, and building type as well as designed heat transfer conditions in the building, designed HVAC systems, and the desired aesthetic performance of the façade and fenestration. Possible positions of the shading device are: in front of the façade, inside the façade, and between the two panes of glass in the double insulated glass unit or the two façade layers in the double-skin façade. The source of measure for the position of the shading device is a database of various positions.

3. Shading device variables: independent or dependent. The shading device variables, such as various blind materials, geometry, width, thickness, position, tilt angle, and distance between the slats, influence the daylight illuminance in the space and the values of the daylight autonomy. At the same time, the design/selection of the shading device variables is directly affected by the performance parameters, such as the required illuminance in the space.

The ***performance parameter*** is a measurable factor that determines the behavior of a shading device. The performance parameter's value varies based on the values of the independent, dependent, and shading device variables. The performance parameters analyzed in this DMF include illuminance and daylight autonomy.

Illuminance is the performance parameter that measures the quantity of light in the space. It is the luminous flux incident on a surface. The SI unit of illuminance is the lux (lx). Illumination of the interior space can be provided from daylighting and electric lighting. The goal is to use daylight to provide the maximum possible illumination level, and then if needed, the remaining illumination needs will be provided by electric lighting. Sources of measures for the required illuminance level in the space are active standards, codes, and recommendations that give the values of the required illuminance based on: the type of the task, the illuminance category of the task, the levels of illumination for safety, the task and background reflectance, and the weighting factors (the age of the occupant and the reflectance of the surfaces). Once the decisions about the building type and tasks performed in the particular building spaces are made, the required values for illuminance can be automatically derived from databases of active standards. The values of illuminance given by the standards are used as a reference in the evaluation of the actual illuminance as a result of the application of a particular shading device.

Daylight autonomy (DA) is the percentage of time per year for which a shading device provides the minimum amount of daylight in the space without the need for electric lighting, provided the amount also does not exceed the maximum values recommended by the standards. DA is calculated based on the actual values of the illuminance levels in the space.

After the DMF components, that is, variables and parameters are identified, the relationships among the components are determined. It is crucial that the user of the DMF understands how the DMF components interact to make the decision about the values of the variables and parameters. Therefore, the line/arrow symbols used in the DMF represent the dependence of one variable or parameter on the other one. For example, climate as an independent variable affects both the façade type and shading device position relative to the façade as the dependent variables. Based on this relationship, the building designer knows that values of climate variables must be considered when making the decision about the façade type and shading device position.

4.2.3. Benefits of Using the DMF Based on Daylighting.

The use of the DMF based on daylighting provides better input in the process of making the decision about the shading device selection/design compared to the current decision-making practices. Currently, building designers rely mostly on their experience when making the decision about shading device selection/design. For example, the designer would consider location and type of building, design, structure, and materials used for the façade. Regarding the shading device performance, designers usually think about protection from heat, providing privacy, aesthetic performance, and cost of the shading devices. In conclusion, designers use aesthetics as the primary criterion for the shading device selection/design, and some parameters of thermal, cost, and visual performance as the secondary criteria. Also, a systematic approach in the decision-making is not common, and decision criteria are used at a general rather than at a more detailed and specific level.

Therefore, this DMF presents a robust method for shading device selection/design. Understanding the structure of the DMF is very important because it helps the user of the DMF to make the appropriate decisions about the values of the variables and performance parameters when analyzing and selecting the shading device system. If the DMF user considers all the variables and parameters (and their subcategories) given in this DMF as well as their interactions, the selected/designed shading devices will have an opportunity to meet the required performance criteria.

The use of the DMF based on daylighting also aims to provide better input for testing the various shading device systems either experimentally or by using simulation software. The input for experimental testing or simulation, which is only one step in the decision-making process, naturally overlaps with some of the input parameters/variables in the DMF. However, not all of the input parameters included in the DMF will be used for the experimental testing or simulation; that is, the DMF input consists of a larger number of parameters compared to the number of input parameters needed for testing. For example, the required values of the performance parameters, such as illuminance, are derived from the standards and recommendations, and are not needed in the shading device experimental or simulation testing. The required values of the performance parameters are used later on, in the analysis of the shading device performance. In this step, actual values of the performance parameters, which are the output of testing obtained by experiment or simulation of a shading device, are compared to the required values, which were the input in the DMF.

Application of the DMF can be particularly useful in the experimental testing of shading devices when the designer can not rely on the software input as in the case of simulation. In the experimental testing, the guide, such as the DMF, provides information about various variables/parameters that the designer needs to consider when testing a shading device and analyzing its performance.

5. TESTING OF THE DMF BASED ON DAYLIGHTING

The DMF based on daylighting was tested to find out if the DMF works. A case study was conducted for a theoretical office building located in Roanoke, Virginia, USA. Three different blind systems were simulated to select the most appropriate blinds for the building:

- Blind system A: Mini Venetian blinds made of grey vinyl with a reflectance of 40%, nontransparent for light (Fig. 5). The vertical distance between the slats is 25 mm, and the slat width is 25 mm. The slats have a curved, concave shape in the cross section. The blinds are in the horizontal position relative to the window and are installed in the interior space. The slats are adjustable (Kays 2006). In this research, three basic slat tilt angles were tested: 0°, 45° and 90° tilt angle.
- Blind system B: The shading device patented by US Patent no. 6,367,937 (Koster 2002). The blinds have a tooth shaped upper surface and a slightly curved, concave bottom surface. The width of the slat is 25 mm while its thickness is 4.8 mm. The distance between the slats is 16 mm. The slats are made of clear plastic with a transparency of 100%. The blinds are in a horizontal, fixed, completely open position (0° tilt angle), installed in the cavity between two panes of glass (Fig. 6).

FIGURE 5. Blind system A: Mini Venetian blinds.

FIGURE 6. Blind system B: Perspective view of the patented blinds.

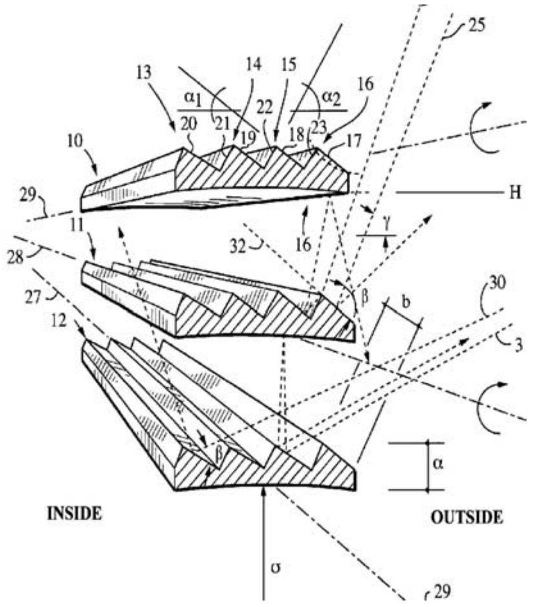
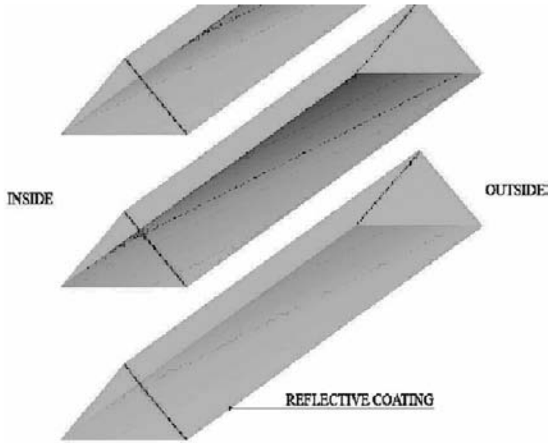


FIGURE 7. Blind system C: Perspective view of the new blinds.



- Blind system C: A new blind system was proposed by this research (Fig. 7). The slat has a right triangular shape in the cross section. The hypotenuse dimension is 25 mm while the triangle legs are 18 mm. The distance between the slats is 25 mm. The slats are made of clear plastic with a transparency of 100% (Haliday and Resnick 1986). A silver, reflective film, 0.5 microns thick and with a 94% reflectance, is applied on the hypotenuse outside surface. The blinds are in the horizontal position relative to the window and installed between the two panes of glass. The blinds are adjustable. The blinds were simulated for three tilt angles: 0°, 45° and 90° tilt angle.

Decision-making frameworks were created for each blind system to identify an input for the simulations. Independent variables, dependent variables, and required illuminance were the same in all three DMFs. The exception was the dependent variable that defines the blinds' position relative to the window, which changed based on the blind system used. Shading device variables were also changed based on the blind system used. An example of the DMF based on the daylighting for blind system A is shown in Figure 8.

An analysis was performed for a rectangular office space 18.3 m wide, 12.2 m deep, and 3 m high (Fig. 9). The south-facing curtain wall had a 55.7 m^2 area and had a completely glazed outside layer. The transparent/windows area was 29.3 m^2, and one window assembly consisted of two parts: lower (1.4 m × 1.5 m) and upper (1.4 m × 0.5 m) and was located 0.9 m above the floor. The opaque parts of the façade had wooden boards as an interior finish with an area of 32 m^2. The window-to-wall ratio was 0.47 while the window-to-floor ratio was 0.13. The blinds were mounted from the window sill to the window top. The office space was divided into separate work spaces by cubicles. Each cubical space contained an office desk, a chair, and a computer. There were shelves and cabinets along the interior walls (Fig. 10). Reflectances of the interior surfaces were based on the choice of the materials.

Simulations of the shading devices were performed for three days per year: December 21, March 21, and June 21; for three times per day: for a south oriented façade at 11:00 a.m., 12:00 p.m., and 3:00 p.m., and for a west oriented façade at 12:00 p.m., 2:00 p.m., and 4:00 p.m.; and for three sky conditions: clear, partly cloudy, and cloudy. The actual illuminance levels were determined for two points in the space:

- The top of the office desk at a distance of 2.4 m from the window
- The top of the office desk at a distance of 8.7 m from the window

FIGURE 8. An example of the DMF based on daylighting for the blind system A.

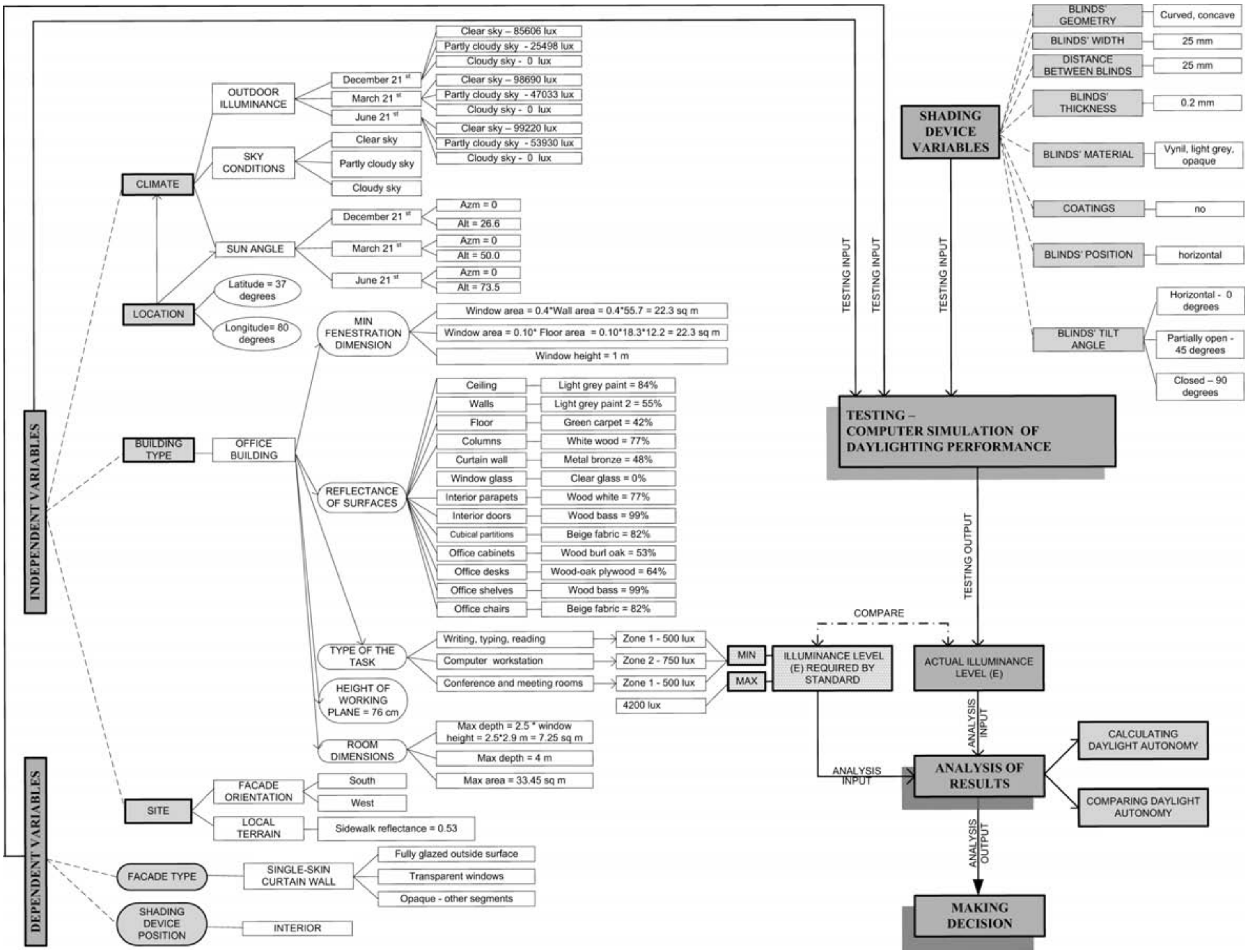


FIGURE 9. Perspective view of the office building.

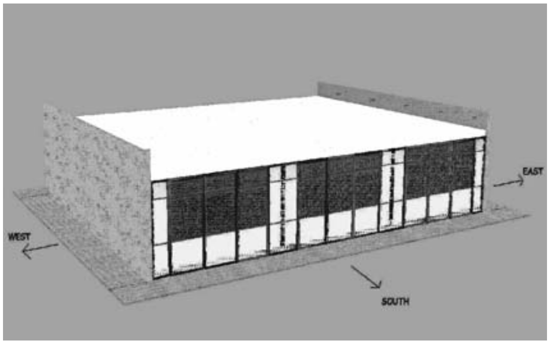
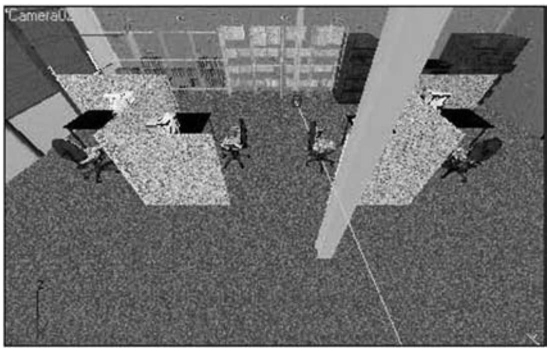


FIGURE 10. Perspective view of the interior space.



The height of the top of the desks' surfaces was 76 cm. The distance between the two measured points was 6.3 m. The required values of illuminance in this office space were taken from the standard and ranged from a minimum of 750 lx to a maximum of 4200 lx.

Autodesk VIZ 4 software was used as a simulation tool in this study. VIZ has a feature that simulates lighting and gives photometric values of illuminance levels in the space. The output of simulation is a photorealistic three-dimensional image of the space with illuminance levels defined by the range of the colors. The user of the DMF inputs the following variables in Autodesk VIZ 4 in order to simulate daylighting:

- A 3D model of the building geometry that includes walls, columns, ceilings, floors, façade/windows, and doors etc.
- A 3D model of the furniture used in the particular space.
- The choice of materials for the interior surfaces and the furniture, which automatically defines the reflectance properties of the materials.
- The camera position and field of view.

The values of these variables remained the same in all the simulations. The following variables were changed in the DMF to present different simulation situations and get different illuminance values by using VIZ 4:

- Shading device: type/geometry (shape, width, and thickness of the slats, distance between the slats), blind material, blind position relative to the window, and slat tilt angle.
- Outdoor conditions: the sun angle changed based on the time (hours, minutes, seconds), date (month, day, year), and location (longitude and latitude). The user of the DMF changed only the time and date in this case study since the location was fixed (Roanoke, Virginia, USA).
- Sky conditions: clear, partly cloudy, cloudy sky.

The analysis of a combination of all these variables required thousands of simulations which resulted in a large quantity of output data that needed to be represented in a simple, organized, and understandable format. The output of the simulation was values of the illuminance levels calculated for different combinations of the input variables. Since the output results were given in the format of the three-dimensional image, the illuminance values were read at different points in the space and recorded in the format of matrixes of the data. These results were then presented in the format of charts that compared daylight autonomy of different blind systems and different sky conditions. The output of simulation, which in this case study was actual illuminance, was compared to the required illuminance. Based on this comparison, the user calculated daylight autonomies for three blind systems, compared them, and made the decision about which blinds to select.

6. RESULTS

6.1. Calculation of Daylight Autonomy (DA)

To compare the performance of different blind systems, the daylight autonomy (DA) for each blind system needs to be calculated. In this case study, the DAs were found for different façade orientations and

TABLE 1. Values of illuminance (lux) taken from the matrixes of data.

Date	Sky conditions	Measurement point	Blind system A	Blind system B	Blind system C
June 21	Clear	Window	1300	1300	2500
		Interior	1300	1300	1700
	Partly cloudy	Window	2500	1800	2500
		Interior	1500	1700	2200
	Cloudy	Window	600	500	1000
		Interior	550	550	650
December 21	Clear	Window	10000	1600	10000
		Interior	1300	850	1800
	Partly cloudy	Window	10000	1100	10000
		Interior	1000	850	1000
	Cloudy	Window	450	400	600
		Interior	400	450	500
March 21	Clear	Window	1700	1600	2500
		Interior	1000	900	1900
	Partly cloudy	Window	2250	1600	2500
		Interior	1300	1000	1600
	Cloudy	Window	500	550	900
		Interior	450	500	600

blind tilt angles. Table 1 presents illuminance data obtained by simulations for:

- Three blind systems (system A, system B, system C)
- Three dates (June 21, December 21, March 21)
- Three sky conditions (clear, partly cloudy, cloudy)
- Two measurement points in the space (top of the desk close to the window, top of the desk close to the interior partition)
- Particular time (for example, 12:00 p.m.)
- Particular façade orientation (for example, south)
- Particular blind tilt angle (for example, 0°)

TABLE 2. Number of days per month for various sky conditions (Roanoke, Virginia, USA).

Month	Sky conditions	Number of days
June	Clear	7
	Partly cloudy	12
	Cloudy	11
December	Clear	9
	Partly cloudy	8
	Cloudy	14
March	Clear	8
	Partly cloudy	9
	Cloudy	14

Table 2 shows the number of clear, partly cloudy, and cloudy days for each month that is simulated, taken from statistical data for Roanoke, Virginia, USA. The values from Tables 1 and 2 were used to calculate daylight autonomy by using the following method:

The values of illuminance from Table 1 were analyzed to see which of them fit in the range of values recommended by the standard (750–4200 lx). The actual value of illuminance met the requirements of the standards for specific sky conditions and on particular days. The number of days per month, for which the required value was obtained, was divided by the total number of days in the month to get the DA per month for that blind system. If the values of actual illuminance are out of the range of values recommended by the standard, that is, less than 750 lx and more than 4200 lx, then the number of days for which these values of illuminance are obtained is multiplied by 0.

Table 3 shows the values of the DA in percentages for each blind system, for each month, and at two measurement points in the space. The values of the DA per month were added up and divided by the number of months to get the average DA value per year in percentages, which is shown in Table 4.

TABLE 3. Daylight autonomy (DA) per month (%).

Month	Measurement point	Blind system A	Blind system B	Blind system C
June	Window	63	63	100
	Interior	63	63	63
December	Window	0	55	0
	Interior	55	55	55
March	Window	55	55	100
	Interior	55	55	55

TABLE 4. Daylight autonomy (DA) per year (%).

Measurement point	Blind system A	Blind system B	Blind system C
Window	39	58	67
Interior	58	58	58

The values of daylight autonomy per year from Table 4 are represented in a chart (Fig. 11, Chart 1), which compares the performance of three blind systems for the south orientation with a 0° blind tilt angle. The horizontal axis shows the measurement points in the space (window, interior), and vertical axis shows the values of the DA per year in percentages.

6.2. Discussion of Results

Six charts (Fig. 11) combine the following factors considered in the analysis of the DA:

- The façade orientation: south or west
- The blind tilt angle: 0°, 45°, 90°
- The measurement point in the space: the top of the desk close to the window or the top of the desk close to the interior partition.

In the analysis of the charts that compare the DA per year for the three blind systems, the following comparisons were performed:

1. An overall comparison of the DA for the three blind systems.
2. A comparison of the DA at two points in the space, for each blind system, for the particular blind tilt angles, and the particular façade orientations.
3. A comparison of the DA for the three blind tilt angles, for each blind system, for a particular point in the space, and the particular façade orientations.
4. A comparison of the DA for two orientations of the façade for each blind system, for a particular point in the space, and the particular blind tilt angle.

An analysis of these charts shows the following results:

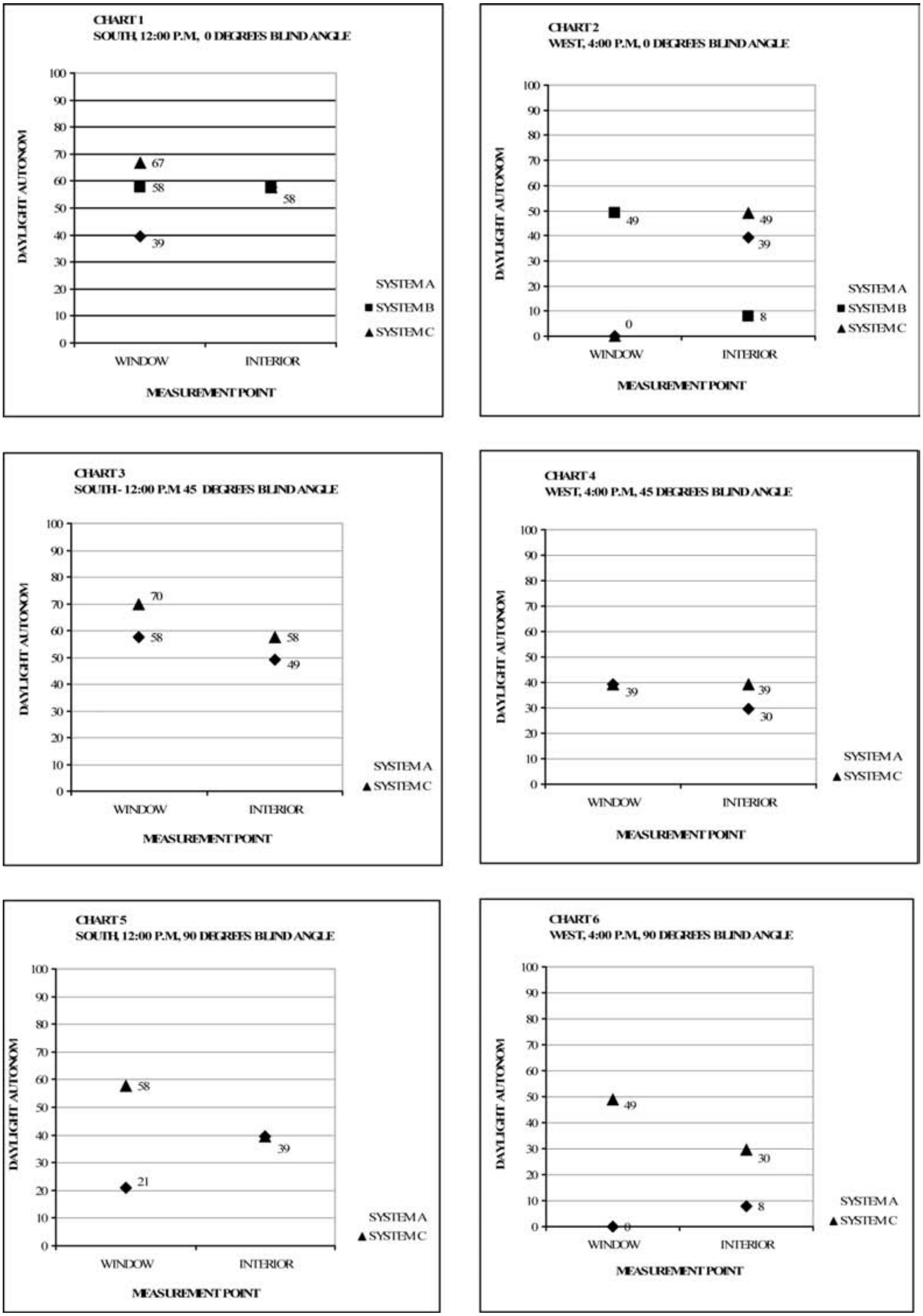
Given the research limitations, blind system C had the highest DA in almost all situations, except at the 0° tilt angle for the west orientation at the measurement point close to the window. When the blinds were set at the 0° tilt angle, the illuminance levels were significantly higher than the maximum level recommended by the standards, so system C could not be kept completely open, resulting in assigning a zero value for the DA. Since system B could have only a 0° tilt angle, its DA could be compared with the DA of the other two systems at only the 0° tilt angle.

Blind system C has a higher DA than blind systems A and B at the south orientation for all the blind tilt angles at the point close to the window. At the point close to the interior, system C has either equal or superior performance compared to the two other blind systems depending on the blind tilt angle. For the west orientation, the DA of system C is higher than that of the other two systems for all tilt angles at the point close to the interior wall. At the point close to the window, system C does not have satisfactory performance for only 0° tilt angle.

System C has the higher DA at the point close to the window, as is predicted for the south orientation and all tilt angles. At the west orientation, system C performs equally or better at the point close to the window for 45° and 90° tilt angles.

At the south orientation, system C has the uniform performance for 0° and 45° tilt angles, and a slightly lower performance at the 90° tilt angle at the

FIGURE 11. Charts for the analysis of DAs for three blind systems, two façade orientations, three blind tilt angles, and two measurement points in the space.



point close to the window. The DA is lower at the point close to the interior for the 90° blinds' tilt angle compared to 0° and 45° tilt angles. At the west orientation, at the point close to the interior, the values of the DA decrease as the blind tilt angle increases.

System C has higher values of the DA for all tilt angles and both measurement points for the south orientation compared to the west orientation.

Blind system B has a higher DA than system A at the south orientation and at the point close to the window at the west orientation. System A performs better at the point close to the interior for the west orientation. System B has a uniform performance at the south-oriented façade for both measurement points. At the west orientation, system B performs better at the point close to the window. System B has the higher DA for the south orientation than for the west orientation.

Given the research limitations, **blind system A** has the lowest DA for all tilt angles, orientations, and measurement points compared to the two other systems, except at the south orientation, at the point close to the interior, for 0° and 90° blind tilt angles when its performance is equal to the performance of the two other systems. System A has the higher DA at the measurement point close to the window than at the point close to interior for the 45° blind tilt angles for both orientations. For 0° and 90° tilt angles, the DA values are lower at the point close to the window. At the point close to the interior for both orientations, the values of the DA decrease as the blind tilt angle increases. System A has a higher DA for the south orientation than for the west orientation for all blind tilt angles and both measurement points.

Given the research limitations, blind system C had the highest DA overall, except for the west orientation at the point close to the window and for the 0° blind tilt angle, and that was the reason for selecting blind system C for the application on the proposed building.

7. CONCLUSIONS

This paper describes the development of the decision-making framework (DMF) for the selection and design of shading devices based on daylighting. The DMF presents the process of analysis of the shading devices' daylighting performance in the selection of existing shading devices currently available on the market, as well as in the design of new shading devices. The research determined the variables that influence the shading device daylight performance and the relationships between the variables. Appropriate daylighting performance measures (such as illuminance and daylight autonomy) were identified and their relationships with variables were described. Interactions among the variables and the effects of these interactions on the shading device daylighting performance were explained and quantified in the DMF. The DMF also included ways of presenting the output information, that is, the results of the simulations and the process of making the decision.

The theoretical testing of the DMF was done by performing a case study in order to validate its functionality. The daylighting performances for three blind systems, installed at an office space in Roanoke, Virginia, USA, were simulated by using the software Autodesk VIZ 4, that calculates illuminance levels. The theoretical testing showed that the DMF works and provides a tool for both the analysis of the daylighting performance of shading devices and for making the decision about the design/selection of the best possible shading device, based on the output information.

The DMF based on daylighting is a useful tool for:

- Building designers: in the selection process for the existing shading device for the specific building at the given location. The DMF can help building designers select the most appropriate shading device based on the imposed daylighting criteria. The DMF helps them understand:
  - — Which methodology to use when making the decision about selecting the best shading device among the several available systems.
  - — Which variables and parameters to consider when analyzing the daylighting performance of the shading device.
  - — How to apply principles of daylighting in the design of the building, the façade, and the shading device from the conceptual phase to the detail phase of design.
- Manufacturers of shading devices: in the process of designing new shading devices. By using the DMF, designers of shading devices are able to un-

derstand the shading device daylighting performance from their design-imposed criteria. The DMF helps manufacturers to understand which variables affect daylighting performance so that they can consider these variables while designing new shading device systems. By using the DMF, the designers of shading devices can improve daylighting performance of new systems in the early design phase.

The DMF developed in this research can also be used as an algorithm for developing a simulation tool in future research. This simulation tool would be used in the process of the selection/design of shading devices based on their daylight performance.

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