Decision-Making Framework for Selection and Design of a Shading Device Based on Daylighting Performance

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ABSTRACT

Application of existing shading devices is limited to protection from overheating and glare and providing privacy. A lack of guidance for appropriate selection and design of the shading device in the windows leads to unsatisfactory performance of the shading device.

The paper explains research that looks to improve performance of a shading device by developing a decision-making framework for selection and design of the shading device systems based on daylighting performance. Goals are to determine daylighting performance required for the shading device and variables that influence shading device daylighting performance and to develop and validate decision-making framework for selection/design of the shading device based on its daylighting performance. A decision-making framework can help designers of the buildings, together with the clients, to select the most appropriate shading device based on daylighting performance and shading device manufacturers to do appropriate design of the new shading device system with improved daylighting performance.

INTRODUCTION

Background

The shading device is an important component of the window, which is part of any conventional façade system as well as curtain wall system (both single-skin and double-skin facade). The shading device provides protection from direct sun and overheating in summer, thus reducing cooling loads for the building. It is also used for providing protection from glare and privacy.

Proper application of the shading device is especially important in the curtain wall systems. Large glass areas are broadly used in contemporary architecture since glass provides direct visual contact between the inside and outside space, which has a significant psychological effect on the building occupants. Glass also contributes to achieving transparent look of the building as well as volume concept as an architectural expression.

Conventional curtain walls (single-skin facades) have been used to achieve these goals, but in the last 20 years double–skin facades have been gaining popularity because of their good thermal properties, ability to control sun radiation, energy efficiency, high acoustical and daylighting performance, and opportunity to provide natural ventilation.

The shading device, as part of the fenestration system, is an important architectural element. Type and position of the shading device system are selected by the building designer based on intuition rather than on performance evaluation of such systems. The shading device can be installed in one of three basic positions:

- In front of the window, i.e., in the exterior space
- Behind the façade, i.e., in the interior space
- Between two glass panes in either:
    - the double insulating glass unit – in which the air cavity is 1/2 in. wide and is a closed, nonventilated system, or

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- the cavity between two glass layers in the double-skin façade—width of the cavity is from a few inches to 3 to 4 feet. The cavity can be either nonventilated or ventilated by moving air naturally or mechanically.

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.

Literature Review

Research on thermal and daylighting performance of various shading devices as a part of fenestration systems was conducted and several calculation models for determining such performance were written. Daylighting performance of venetian blinds depends on the angle of incidence as well as 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 the flat slats will transmit light in a forward direction (Breitenbach et al. 2001). A daylighting simulation model that can predict performance at the normal angle of incidence was developed. 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 (Breitenbach et al. 2001).

The research on an integrated approach to solar control techniques was conducted in order to investigate performance of the shading device systems. Goal was to provide information that is needed to support the industry and the final user of the shading device systems. The final products of research would be a proposal on testing standards for shading devices, upgrade of the existing simulation models, design of a smart solar control assembly, and design guidelines and shading component handbook (Scuito et al. 1998).

The research on the advantages of application of a dynamic venetian blind compared to a fixed blind showed that a dynamic system always blocks direct sun, provides view when there is no direct sun (maximum view was possible for at least 50% of the day throughout the year), and provides controlled illuminance level throughout the day (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 design illuminance level in the space. As a result of this strategy, electric lighting and cooling energy savings were significant (DiBartolomeo et al. 1996).

In providing a sufficient amount of daylighting in the space and protection from overheating, shading device control systems should be designed properly. Dynamic venetian blinds contribute to cooling load reductions and daily lighting energy savings, especially if dimmable daylighting controls were used, although most state energy codes require minimum stepped, dual-level manual switching. For manual operation with fully retracted blinds, lighting savings would be decreased and cooling loads would increase (Lee et al. 1998) Comparison between the between-pane and external dynamic blinds shows that approximately the same lighting energy saving can be accomplished by applications of both systems (Lee et al. 1998).

Problems of State of the Art

Existing shading devices currently available in the market have limited usage. They are usually applied for protection from overheating in summer, for protection from glare, and for providing privacy. The shading devices are very rarely used as solar collectors. The shading device installed in the cavity of the double-skin facade or airflow windows can absorb solar energy and transfer it to the air in the cavity. This warm air can be supplied to the HVAC system in winter or exhausted from the cavity to the outside space in summer. The shading device is rarely used as a thermal barrier. If the shading device blinds are insulated and in the closed position, they can be very effective thermal protection on winter nights. The shading device is not often used as a daylighting system. It can redirect sunlight to the spaces where daylight is needed, such as spaces that have large distance from the window wall, and avoid occurrence of glare. Another problem is that the shading device slats are usually made of nontransparent materials. If the blinds are in closed or partially closed/open position, direct view to the outside is obstructed and transparency of façade is not achieved. There is also a problem with appropriate control systems used to adjust the blind position. If control of blind adjustment is manual, problems can occur if occupants are absent from the room when blinds need to be adjusted. Also, occupants very often close the blinds completely to protect the space from overheating and glare, but at the same time the amount of daylight in the space is reduced and use of electric lighting is increased. As a result, cooling loads are also increased. Balance between sufficient amount of daylight and maximum overheating protection can hardly be achieved without application of automatic control systems.

The significant problem is the lack of specific guidance for analysis of the shading device performance in the process of the selection of the existing shading device system and the design of the new shading device system.

This paper explains research that looks to improve performance of a shading device by developing a decision-making framework (DMF) for the selection and design of the shading device systems in the windows.

OBJECTIVES

The purpose of this research was to study and try to improve the daylighting performance of a shading device as a part of the fenestration by developing a decision-making framework (DMF) that will be used as an analysis tool in the process of selection of the existing shading device system, performed by the building designer as well as in the process of the design of the new shading device system, done by the manufacturer. DMF is based only on the daylighting performance of the shading device. Objectives of the research are as follows:

1. Determine variables that affect performance of the shading device (such as independent, dependent, and shading device variables) and specifically, at a more detailed level, variables that affect daylighting performance
2. Determine performance requirements for the shading devices, such as thermal, visual, aesthetic, control, and cost performance, and specifically, at a detailed level, daylighting performance parameters, such as illuminance and luminance
3. Identify measures for variables and daylighting performance parameters and sources of measures
4. Develop DMF for the shading device selection and design based on daylighting performance requirements and defined variables that influence performance as well as interactions among them
5. Validate DMF

METHODOLOGY

In order to accomplish research objectives the following tasks were performed:

1. Objective 1—Tasks were to categorize variables that affect shading device performance, determine possible variables for each category, and determine relationships and interactions among variables.
2. Objective 2—Tasks were to categorize possible performance requirements for the shading devices, define variables related to the specific performance, determine interactions and relationships among variables and performance requirements.
3. Objective 3—Task was to identify measures, i.e., values and units as well as sources of measures for each variable and daylighting performance parameter.
4. Objective 4—Tasks were to:
    - define decision problem,
    - develop the influence diagram and the decision-making tree/chart,
    - define input and output parameters of DMF and relationship among them,
    - describe process of making decision based on output data.
5. Objective 5—Tasks were to:
    - validate DMF for the selection of the shading devices by running the model for
        - existing shading device system,
        - patented shading device system and for particular type of the building and building location, and
    - validate decision-making framework for the design of the shading devices based on its daylighting performance, by running the model for the new shading device system in order to test its daylighting performance and DMF at the same time.

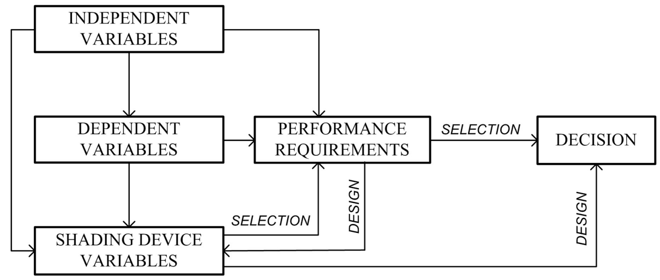

Figure 1 *Simplified diagram of the decision-making framework.*

RESULTS

Decision-Making Framework (DMF)

The first result accomplished for the first and second research objectives is the global DMF that includes possible variables and performance requirements and defines relationships and interactions among them in general, rather than in detail. Simplified diagram of the global DMF is shown in Figure 1. By expanding the simplified diagram and adding more details, i.e., defining subcategories for each major variable and performance requirement, a global, complex DMF for the shading device selection and design was developed.

The global DMF is shown in Figure 2. 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. They are independent in the process of the selection of the existing shading device system 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 system because the designer of the shading device determines shading device variables. Performance requirements considered in the global DMF are thermal, visual, aesthetic, control, and cost, including possible parameters for each performance requirement. The global DMF shows the complexity of the problem and need to focus research on only 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 2, showing that research focuses particularly on daylighting illuminance and luminance as performance parameters relevant in selection/design of the shading device.

The main result of research is the DMF based on the shading device daylighting performance shown in Figure 3. This DMF is accomplishment of objectives 1-4 of research and includes:

1. **Possible variables (independent, dependent, and shading device variables) developed in detail.**

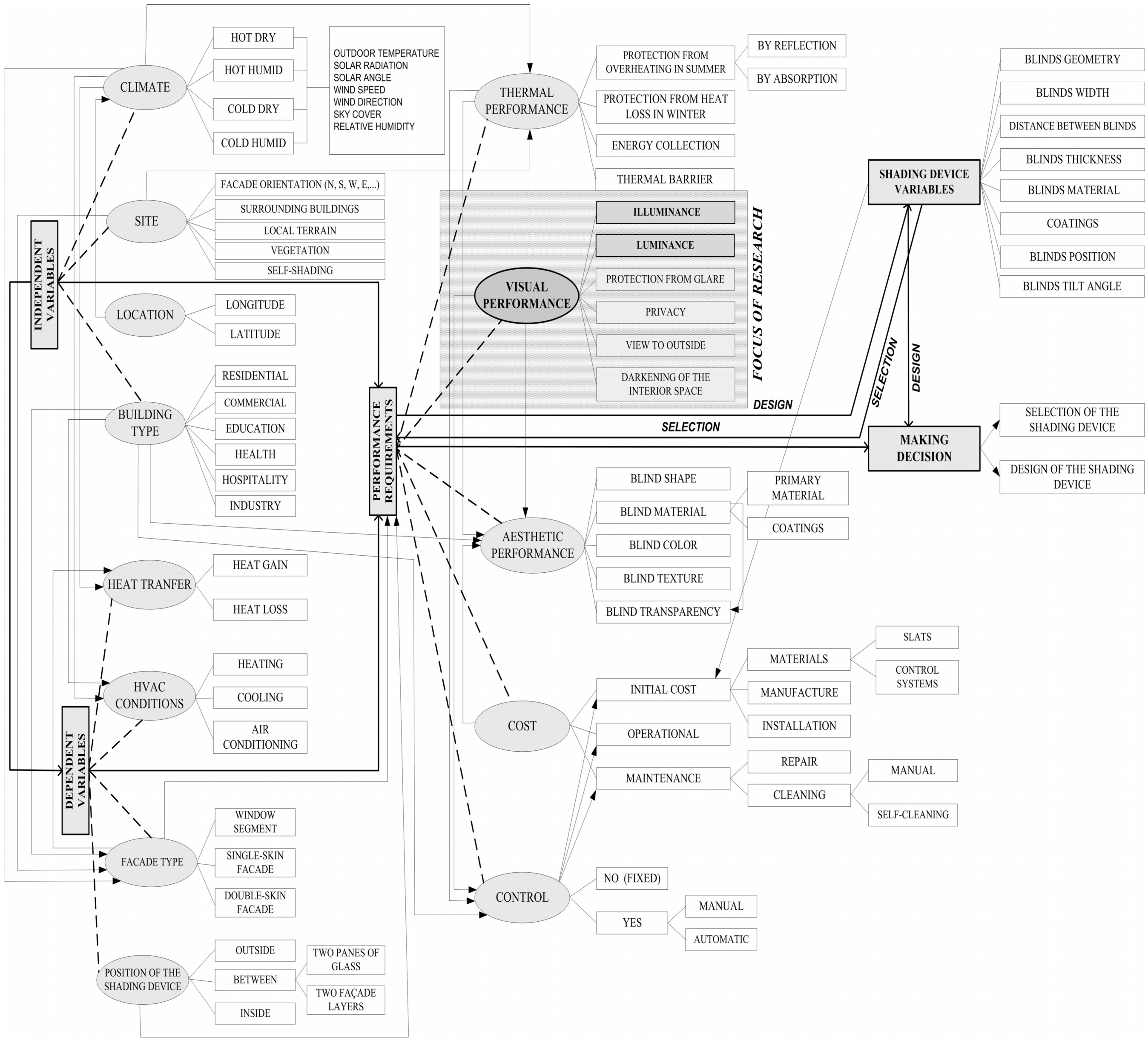

Figure 2 *Global decision-making framework.*

Independent variables included climate, site, and building type.

Climate is determined by the building location. DMF includes the following climate parameters that influence daylighting performance of the shading devices: outdoor illuminance, sky conditions, and sun angle. Sources of the measures for climate parameters can be

- experimental measurements for the particular site,
- statistical climate data for particular weather station,
- mathematical calculations.

Building site directly influences microclimate and daylighting performance of the shading device system. In the DMF the following site parameters are considered in relation to the daylight performance: existing, surrounding buildings, influence of the site on façade orientation, local terrain, vegetation, and self-shading. Sources of measures are databases developed for the each site parameter.

Building type directly affects dependent variables such as façade type and shading device variables. Building type also influences the following parameters: fenestration dimension and position in wall, reflectance of interior surfaces, room dimensions, and height of the working plane as well as type of the tasks performed in the building. Based on the types of the

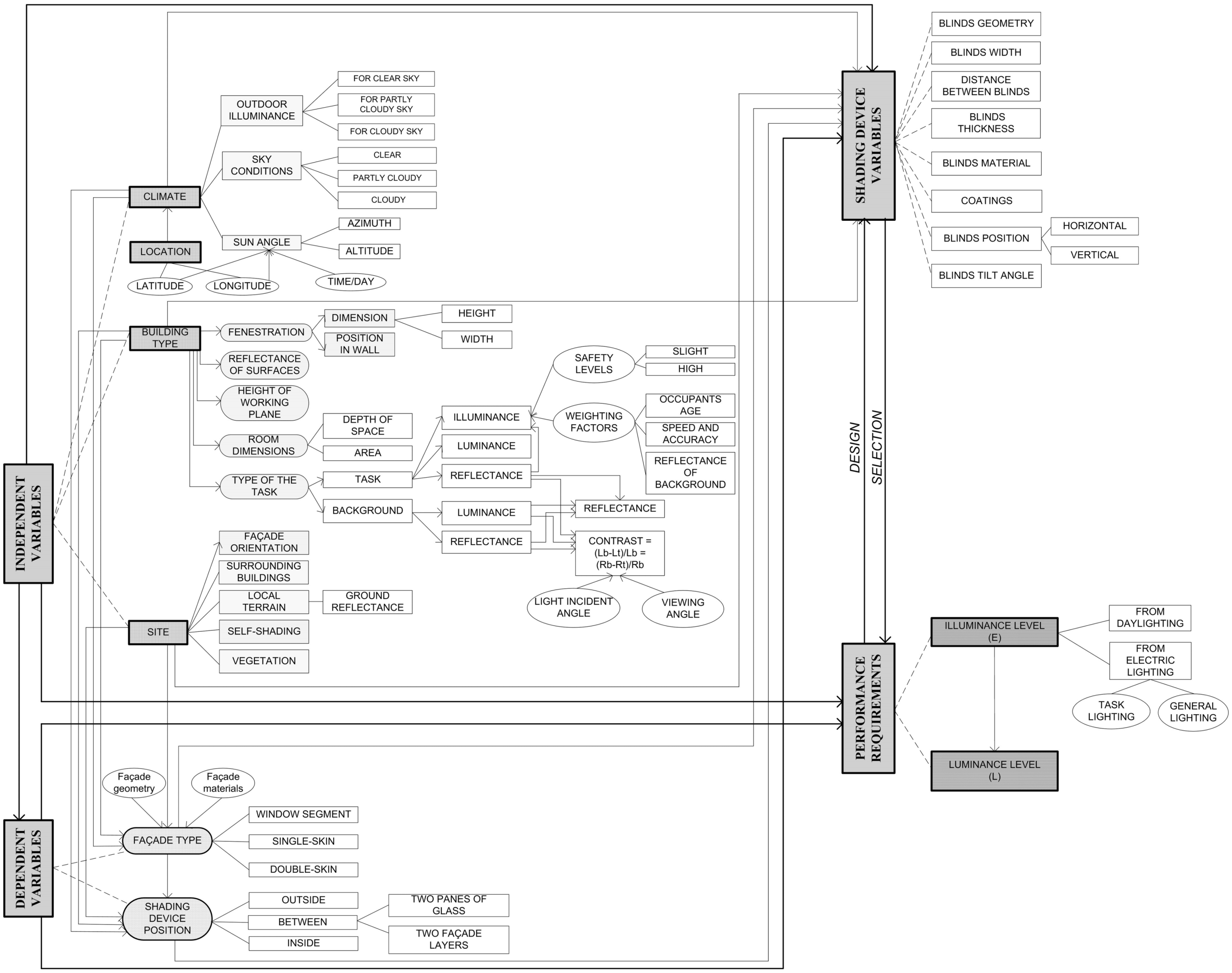

Figure 3 *Decision-making framework based on shading device daylighting performance.*

tasks, required daylight performance of the shading device can be determined by active standards, codes, and recommendations. Source of measures for the building type is database of various possible building types. This database is linked to a database of possible tasks that can be performed in the particular space.

Dependent variables are directly affected by independent variables. The following dependent variables are designer's choice in DMF: façade type and position of the shading device in the façade. Choice of the façade type depends on climate, site, and building type and it can be the window in the conventional wall or in the curtain wall (single-skin and/or double-skin façade). Application of the specific shading device system in the window depends on façade geometry and applied façade materials. Sources of measures for façade types are databases of various types of facades depending on their structure, applied materials, and geometry. Position of the shading device in the façade depends on climate, site, and building type (independent variables) as well as designed heat transfer conditions in the building and designed HVAC systems, which are also designer's choice. Position of the shading device also depends on the desired aesthetic performance of the façade and fenestration. Possible positions of the shading device in the façade given in the DMF are: outside, in front of façade, inside the façade, in the interior space, and between either two panes of glass in double insulated glass unit or two façade layers in double-skin façade. Source of measure for the position of shading device is a database of various positions.

Shading device variables considered in the framework were: blind geometry, width, thickness, materials and coatings, distance between blinds, blind position, as well as their tilt angle.

2. **Performance parameters for shading device system such as illuminance and luminance.**

   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. Goal is to use daylight to provide maximum possible illumination level and then the rest of the illumination should be provided by electric lighting. Sources of measures for illuminance level in the space are active standards, codes, and recommendations that give values of needed illumination level based on: type of the task, illuminance category of the task, levels of illumination for safety, task and background reflectance, and weighting factors (age of occupant, reflectance of surfaces).

   Luminance is the performance parameter that measures the quantity of light reflected off a surface in a particular direction. The SI unit of luminance is candela per square meter (cd/m^2). Sources of measures for luminance are also standards, codes, and recommendations.

Once the decision about building type and tasks performed in the particular building spaces are made, recommended values for daylighting performance parameters can be automatically derived from databases of active standards. Values of daylighting performance parameters given by standards are used as a reference in the evaluation of actual daylighting performance of the particular shading device system.

Actual daylighting performance can be determined either experimentally or by using ray-tracing software. For the purpose of this research and the need to do multiple testing of the various shading device systems in order to decide which one performs best for the particular climate conditions and building type, application of computer simulation is more efficient.

Values of independent, dependent, and shading device variables are used as an input for the DMF. This input can be used for either experimental testing or computer simulation of the particular shading device daylighting performance. Testing for the same shading device can be repeated several times for various sun angles, sky conditions, and outdoor illuminance as well as blind tilt angle, which can give different shading device daylighting performances.

Output of the experimental testing or computer simulation is the actual performance of specific shading device, i.e., actual illuminance and luminance level in specific space of the building and for particular building location and climate.

In the final step of the decision-making process, output of the computer simulation or experimental testing, i.e., values of actual performance of the shading device, are compared to the required performance proposed by the standards. Based on these comparisons, a decision about application of the shading device is made. If actual values are within the recommended range of values, then the shading device performance meets proposed requirements and the shading device can be applied on the specific building.

Validation Process – Case Study Description. A case study was performed in order to validate DMF. Three shading device systems were simulated by computer software:

- ***Existing system*** **-** Mini venetian blinds made of grey vinyl with reflectance of 40%, nontransparent for light. Vertical distance between the blinds is 1 inch and the slat width is 1 inch. The slat has a curved, concave shape in cross section. The blinds are in the horizontal position relative to the window and are installed in the interior space. The slats are operable. In the research, three basic positions of this type blind are tested: completely open (0° tilt angle), partially open/partially closed (45° tilt angle), and completely closed (90° tilt angle).
- ***Patented system*** **-** The shading device patented by U.S. Patent no. 6,367,937. The blinds have a tooth-shaped upper surface and slightly curved, concave bottom surface. Width of the slat is 1 in. while its thickness is 3/16 in. Distance between the slats is 0.625 inch. The slats are made of clear plastic with transparency of 100%. The blinds are always in horizontal, fixed, completely open position (0° tilt angle), installed in the cavity between two panes of glass.
- ***New system*** **-** New shading device system has been proposed by this research. The slat has a right triangle shape in the cross section. Hypotenuse dimension is 1 inch, while triangle legs are 0.707 inch. Distance between the slats is 1 inch. The slats are made of clear plastic with transparency of 100%. Silver, reflective film 0.5 microns thick and 94% reflective is applied on the hypotenuse outside surface. The blinds are in the horizontal position relative to the window and installed between two panes of the glass. The blinds are simulated for three tilt angles in this research: 0° tilt angle (completely open blinds), 45° tilt angle (partially open/ partially closed blinds), 90° tilt angle (completely closed blinds).

Figure 4 shows an example of application of DMF for the selection of the shading device with the best daylighting performance among three offered alternatives. An example shows DMF for the new system of the blinds. The similar DMF layout is used for two other systems of the blinds: existing and patented. Independent and dependent variables that are the input for the DMF are the same in all three cases with the exception of the blind position relative to the window. Shading device variables are changed based on the type of the blinds.

A proposed office building used in the case study is located in Roanoke, Virginia, which has a moderate climate. Analysis is done for a rectangular office space 60 ft wide, 40 ft deep, and 10 ft high. The south-facing curtain wall has 600 ft^2

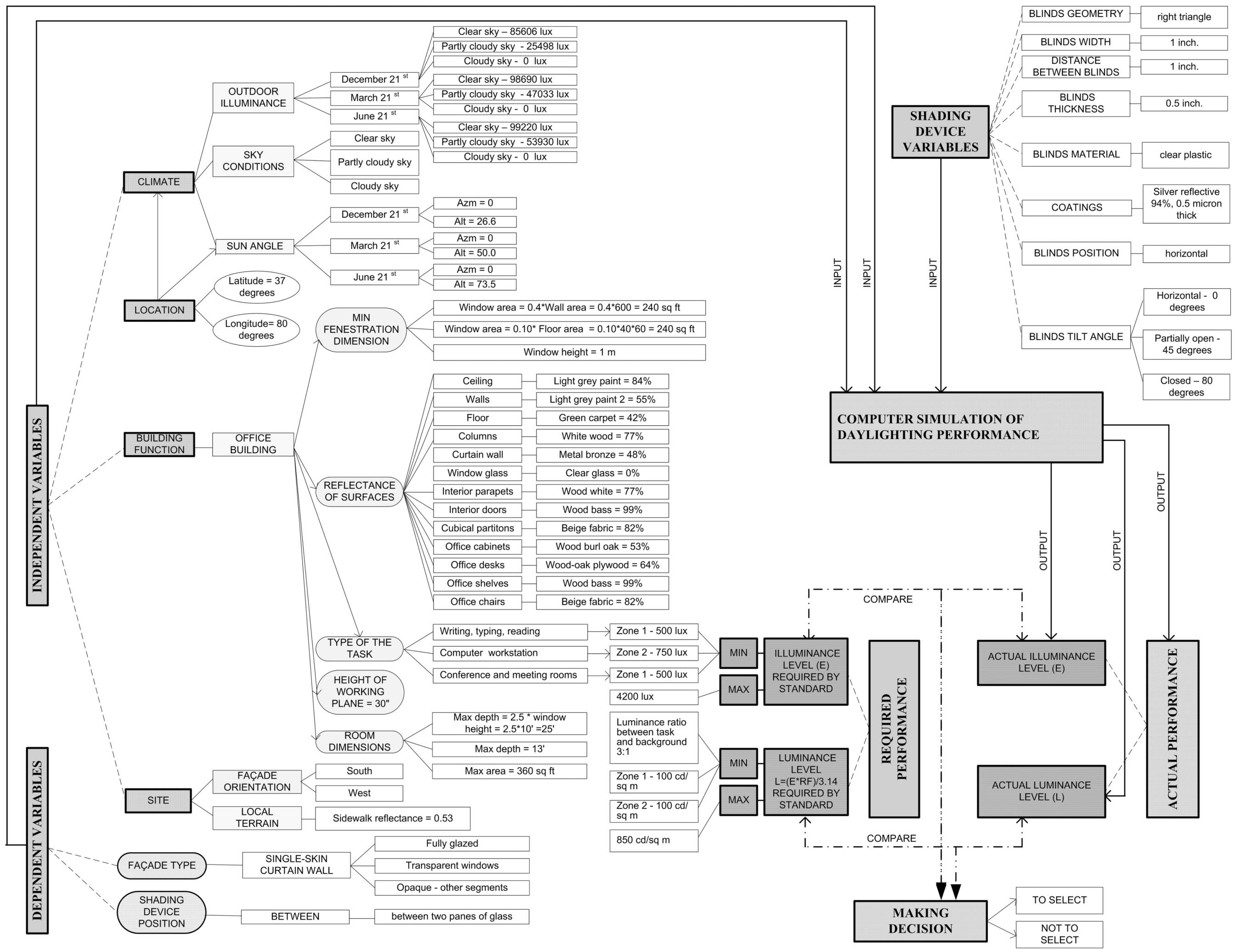

Figure 4 *An example of application of DMF for selection of new shading device system at the office building in Roanoke, Va.*

area and has completely glazed outside layer. Transparent/ windows area is 315 ft^2 and one window assembly consists of two parts: lower (4.5 ft × 5 ft) and upper (4.5 ft × 1.75 ft) and is located 3 ft above the floor. Opaque parts of the façade have wooden boards as an interior finish and area of 345 ft^2. The window-to-wall ratio is 0.47 while window-to-floor ratio is 0.13. The office space is divided into separate work spaces by cubicles. Each cubicle space contains the office desk, chair, and computer. There are shelves and cabinets along the interior walls. Reflectances of the interior surfaces are based on the choice of 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 south-oriented façade at 9:00 a.m., 12:00 p.m., and 3:00 p.m., and for 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.

Two performance parameters are measured by the simulations: illuminance and luminance. Both illuminance and luminance are determined for two points in the space:

- The office desk at 96 in. from the window; height of the top of the surface is 30 in.
- The office desk at 343 in. from the window; height of the top of the surface is 30 in.

Distance between two measured points is 247 inch.

Method of analysis - Software Autodesk VIZ 4, which has a feature that simulates lighting and gives photometric values of illuminance and luminance levels in the space, was used as a simulation tool in this study. Output is photorealistic three-dimensional image of the space with levels defined by the range of the colors. The user of the DMF needs to input the following, fixed parameters in Autodesk VIZ 4 in order to simulate daylighting:

Table 1. Sky Conditions—Number of Days

Month	Clear	Partly Cloudy	Cloudy
January	8	8	15
February	8	7	13
March	8	9	14
April	8	9	13
May	7	11	13
June	7	12	11
July	7	13	11
August	8	12	11
September	10	9	11
October	13	7	11
November	9	8	13
December	9	8	14
Annual	102	113	151

- Building geometry: walls, columns, ceilings, floors, façade/windows, doors, etc.
- Furniture specific for the particular type of the space
- Choice of materials for interior surfaces and furniture that automatically defines reflectance properties of materials
- Camera position and field of view

The following parameters were varied in order to get different performance parameter values (illuminance and luminance) 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 blind tilt angle
- Outdoor conditions: sun angle – changes based on time (hours, minutes, seconds), date (month, day, year), and location (longitude and latitude). The user of DMF in this case study changes just time and date, since location is fixed (Roanoke, Virginia).
- Sky conditions: clear, partly cloudy, cloudy

Presentation of results – Matrixes of data and charts were used to present results of the simulation in this case study. This format of data shows average annual illuminance-days and luminance-days for each type of blind as well as range of the values recommended by the standard and for three different sky conditions. In this way presentation of data is simplified and made more applicable and helpful for the user of the DMF (see Tables 1-5). By comparing values of illuminance-days and luminance-days for three type of blind the user of DMF can conclude which type of blind provides the illuminance (or luminance) levels required by the standard for the longest period of time (i.e., number of days per month or year). The shading device system that shows the best daylighting performance for the longest time, i.e., the highest values of illuminance-days/year and luminance-days/year should be applied on the building.

Table 1 shows the number of clear, partly cloudy, and cloudy days per month and per year for Roanoke, Virginia. Table 2 shows illuminance values at the points close to the window and for each type of blind, for three sky conditions, and for each month in the year as well as annually. Illuminance values in these tables are calculated for March 21, June 21, and December 21 for specific blind position and tilt angle. There are eight sets of these five tables and the chart, and each set represents a combination of the following parameters:

- Performance parameters – illuminance/luminance
- Orientation of the façade – south/west
- Point at which the measurements are taken – close to the window/close to the interior partition wall

Average values are found by summarizing values for a particular month for three hours per day and for particular sky conditions. Since the illuminance values are calculated only for March, June, and December by using VIZ 4, the values for other months are found by interpolation of the known values.

Table 3 shows average illuminance-day values for each type of blind and three sky conditions and for each month in the year as well as annual values. Values in this table are calculated by multiplying average values for illuminance (Table 2) and number of days for various sky conditions (Table 1) for each type of blind. Values are found for each month and the total for the year by adding values for 12 months.

Table 4 presents annual values of illuminance-days for each type of blind and for three sky conditions. It also gives minimum and maximum values that are recommended by the standard:

- For illuminance-days – 90000 (lx*days) – minimum value is calculated by using the following formula: [min illuminance (by standard)] × (average number of days/month for particular sky condition) × 12 months = (750 lx) × (10 days) × 12 = 90000 lx*days/year
- For luminance-days – 12000 [(cd/m^2)*days] – minimum value is calculated by using the following formula: [min luminance (by standard)] × (average number of days/month for particular sky condition) × 12 months = (100 cd/m^2) × (10 days) × 12 = 12000 (cd/m^2)*days/year

Maximum values for illuminance-days and luminance-days are calculated in the same way, using maximum illuminance value of 4200 lx and maximum luminance value of 850 cd/m^2 recommended by the standard. Annual values for illuminance are just taken from Table 3. Table 5 presents the same

Table 2. Illuminance at the Point Close to the Window (lx)

Month	Existing Blinds			Patented Blinds			New Blinds		
	Clear	Partly Cloudy	Cloudy	Clear	Partly Cloudy	Cloudy	Clear	Partly Cloudy	Cloudy
January	1433	889	394	1700	1147	333	2444	2022	628
February	1300	1028	439	1600	1273	400	2456	2211	706
March	1167	1167	483	1500	1400	467	2467	2400	783
April	1189	1178	517	1456	1400	467	2378	2367	828
May	1211	1189	550	1411	1400	467	2289	2333	872
June	1233	1200	583	1367	1400	467	2200	2300	917
July	1211	1189	550	1411	1400	467	2289	2333	872
August	1189	1178	516	1456	1400	467	2378	2367	828
September	1167	1167	483	1500	1400	467	2467	2400	783
October	1300	1028	439	1600	1273	400	2456	2211	705
November	1433	889	394	1700	1147	333	2445	2022	628
December	1567	750	350	1800	1020	267	2433	1833	550
Annual	15401	12851	5699	18500	15660	5001	28701	26800	9099

Table 3. Illuminance × Days at the Point Close to the Window (lx*days)

Month	Existing Blinds			Patented Blinds			New Blinds		
	Clear	Partly Cloudy	Cloudy	Clear	Partly Cloudy	Cloudy	Clear	Partly Cloudy	Cloudy
January	11467	7111	5917	13600	9173	5000	19556	16178	9417
February	10400	7194	5706	12800	8913	5200	19644	15478	9172
March	9333	10500	6767	12000	12600	6533	19733	21600	10967
April	9511	10600	6717	11644	12600	6067	19022	21300	10761
May	8478	13078	7150	9878	15400	6067	16022	25667	11339
June	8633	14400	6417	9567	16800	5133	15400	27600	10083
July	8479	15457	6049	9878	18200	5135	16023	30333	9593
August	9513	14136	5681	11644	16800	5136	19024	28400	9103
September	11670	10503	5313	15000	12600	5137	24670	21600	8613
October	16903	7196	4825	20800	8913	4402	31925	15478	7759
November	12901	7112	5126	15300	9173	4335	22001	16178	8160
December	14100	6000	4900	16200	8160	3733	21900	14667	7700
Annual	131388	123287	70567	158311	149333	61878	244921	254478	112667

Table 4. Annual Illuminance × Days (lx*days/year)

	Clear	Partly Cloudy	Cloudy
existing	131388	123287	70567
patented	158311	149333	61878
new	244921	254478	112667
minimum standard	90000	90000	90000
maximum standard	504000	504000	504000

Table 5. Annual Illuminance × Days (K lx*days/year)

	Clear	Partly Cloudy	Cloudy
existing	131	123	71
patented	158	149	62
new	245	254	113
minimum standard	90	90	90
maximum standard	504	504	504

values as Table 4 just given in K lx*day for more convenient presentation of the data in the line chart.

The chart shows comparison of the annual daylighting performance among three types of blinds for clear, partly cloudy, and cloudy skies. Sky conditions are shown on horizontal (x) axis while vertical (y) axis shows values of annual illuminance-days (in K lx*days).

DISCUSSION OF RESULTS

Analysis of Results

By analysis of the charts for illuminance (Figure 6) and luminance (Figure 7) the user of DMF can decide which type of blind has the best performance. Charts shown in Figure 6 present values of illuminance*days/year for three types of blinds (existing, patented, new), for three sky conditions (clear, partly cloudy, cloudy), for south and west orientation and two points in the space (window desk and interior desk).

Chart 1 shows that new blinds give the highest values of illuminance-days/year (ill-days/year) for all sky conditions compared to patented and existing blinds at the south orientation and at the desk close to the window. Patented blinds give higher values of ill-days/year for clear and partly cloudy sky compared to existing blinds, while existing blinds perform better then patented blinds for cloudy sky. All three types of blind meet requirements of the standard for the minimum ill-days/year for clear and partly cloudy sky, while only new blinds meet minimum requirements of the standard for the cloudy sky conditions. Chart 1 illustrates that sky conditions have significant effect on the performance of all three types of blind. Values of ill-days/year do not differ significantly for clear and partly cloudy sky for all three types of the blinds, but

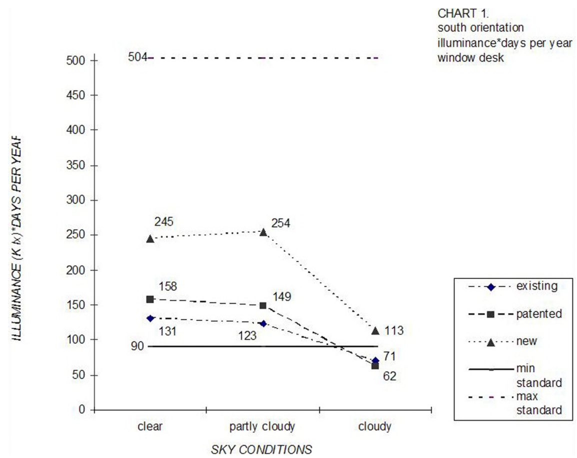

*Figure 5 Relationship between illuminance*days/year levels and sky conditions for three types of the blinds.*

they have significantly lower performance (approximately 50%) for cloudy sky conditions.

Chart 2 illustrates performance of three types of blind at the south-oriented façade and for measurements taken at the desk close to the interior partition wall. New blinds show the best performance compared to existing and patented blinds for all sky conditions. Existing blinds show better performance then patented blinds for clear sky conditions, while patented blinds perform better then existing blinds for partly cloudy and cloudy sky. All three types of blind meet requirements of standards for clear and partly cloudy sky, and none of them for cloudy sky. All three types of blind show higher value of ill-days/year for partly cloudy sky than for clear sky, while values of their performance for cloudy sky are 50% lower compared to partly cloudy sky conditions.

Chart 3 shows performance of three types of blind oriented to the west with measurements made at the desk close to the window. New blinds perform significantly better than patented and existing blinds for all sky conditions, while patented blinds show slightly better performance then existing binds for clear and partly cloudy sky. Existing blinds perform better than patented blinds for cloudy sky. Only new blinds meet minimum requirements of the standard for all sky conditions, while patented and existing blinds meet minimum requirements for clear and partly cloudy sky, but not for cloudy sky. Cloudy sky significantly affects performance of all three types of blind. Values of ill-days/year are 50% lower for the cloudy sky than for the partly cloudy and clear sky.

Chart 4 illustrates performance of the blinds oriented to the west and measurements taken at the top of the desk close to the interior wall. New blinds show the highest values of ill-days/year compared to patented and existing systems, for all sky conditions. Patented blinds perform slightly better than existing blinds for all sky conditions. All three types of blind meet minimum performance requirements of standards for

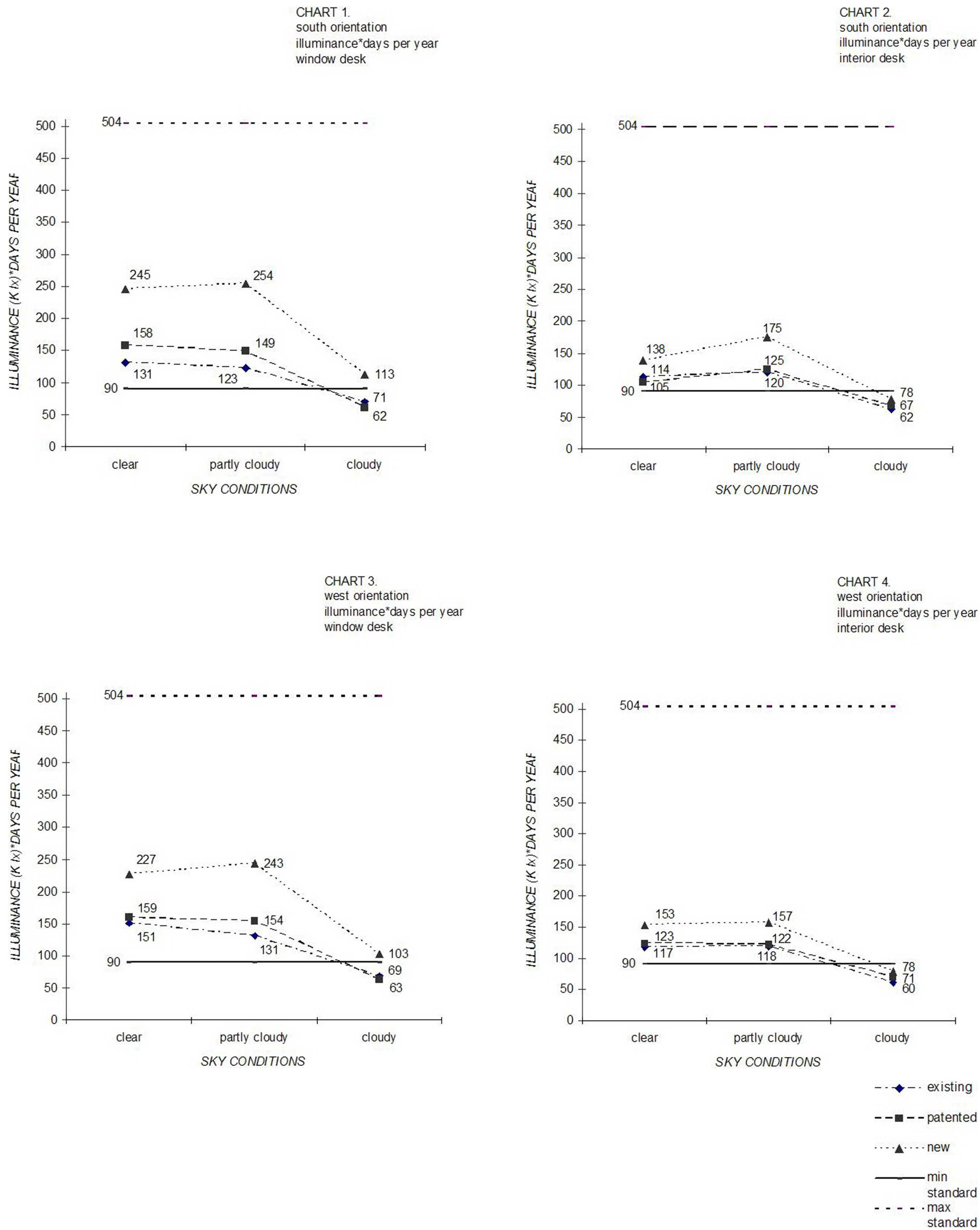

Figure 6 *Relationship between illuminance-day levels and sky conditions for three types of the blinds.*

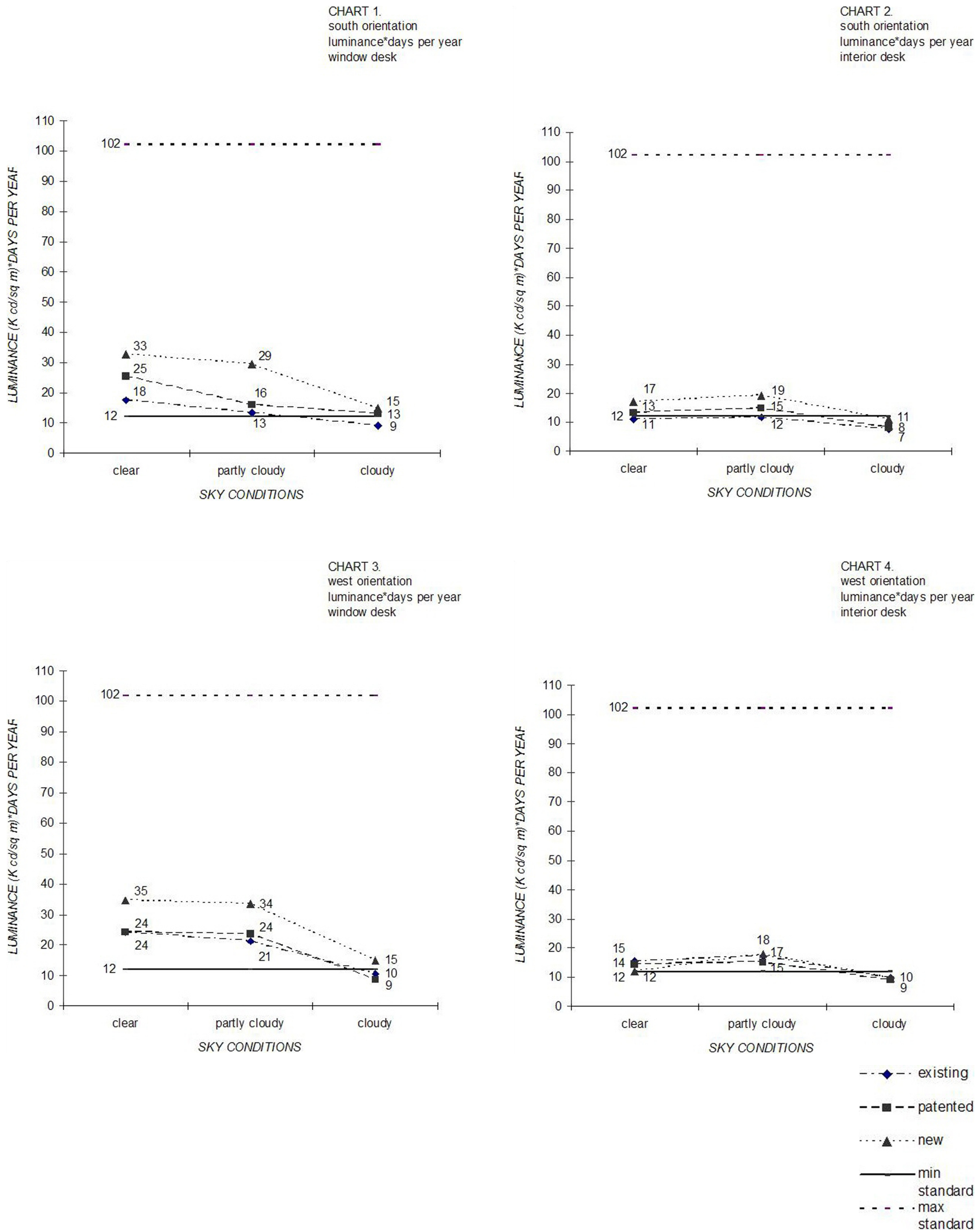

__Figure 7__ Relationship between luminance-day levels and sky conditions for three types of the blinds.

clear and partly cloudy conditions, but they do not meet minimum requirements for cloudy sky conditions. All three types of blind show almost the same performance for clear and partly cloudy sky, but values of ill-days/year drop 50% for cloudy sky.

Comparison between south and west oriented blinds shows that:

- New blinds perform slightly better for south orientation at the point close to the window for all sky conditions. At the point close to the interior wall, values of ill-day/year are the same for cloudy sky, higher for the partly cloudy sky at the south-oriented façade, and higher for clear sky at west-oriented façade.
- Patented blinds show almost the same performance for the south and west orientations for all sky conditions at the point close to the window. At the point close to the interior wall, patented blinds have almost the same performance at south and west orientation for partly cloudy and cloudy sky, while for clear sky they perform better at west orientation.
- Existing blinds at the point close to the window show better performance for clear and partly cloudy sky at west orientation and almost the same performance for cloudy sky at south and west orientation. At the point close to the interior wall, existing blinds have almost the same performance at south and west orientation.

Comparison of values of ill-days/year at two measured points show that for both orientations highest values are achieved at the point close to the window for all three types of blind for clear and partly cloudy sky. For cloudy sky, values of ill-days/year slightly differ between two points for patented and existing blinds regardless of their orientation, while new blinds show 30% lower values of ill-days/year at the point close to the interior wall.

Analysis of four charts in Figure 6 shows that new blinds give the highest values of ill-days/year compared to other two types of blinds. New blinds meet minimum requirements of the standards for all sky conditions at the point close to the window and do not meet minimum requirements only for cloudy sky conditions at the point close to the interior wall. It means that daylight will be sufficient for most of the time except for cloudy sky, for which electric light will be needed only in the depth of the space, close to the interior partition wall.

Charts in Figure 7 show values of luminance-days/year (lum-days/year) for three types of blind, three sky conditions, two orientations, and two points in the space. Analysis of Chart 1 shows that new blind application gives the highest value of lum-days/year at the point close to the window for south orientation compared to existing and patented blinds for all sky conditions. Patented blinds give higher values of lum-days/year than existing blinds for all sky conditions. All three types of the blinds meet requirements of the standards for min values of lum-days/year in clear and partly cloudy sky conditions. Values of lum-days/year obtained by new and patented blinds in cloudy sky are higher than minimum values recommended by the standards. New and patented blind performance in the cloudy sky conditions are higher than minimum values recommended by the standards, while existing blind performance does not meet requirements of standards for the minimum lum-days/year in cloudy sky. Sky conditions affect values of lum-days/year for all three types of blind. The highest values are obtained in the clear sky conditions, while the lowest values are achieved in cloudy sky.

Chart 2 (Figure 7) shows performance of the blinds at the point close to the interior partition wall for the south-oriented façade. New blinds provide the highest value of lum-days/year for all sky conditions compared to patented and existing blinds. Patented blinds have better performance than existing blinds for all sky conditions. New and patented blind performance meet requirements of the standards for minimum lum-days/year values for clear and partly cloudy sky but do not meet minimum requirements for cloudy sky. Existing blinds meet minimum requirements of the standards for only partly cloudy sky. Sky conditions affect performance of the blinds: values of lum-days/year are the highest in partly cloudy sky for all three types of blind, while values in the clear sky conditions are higher than values in the cloudy sky.

Chart 3 in Figure 7 illustrates values of lum-days/year for blinds installed at west-oriented façade with measurements taken at the point close to the window. The highest values are achieved by new blinds in all sky conditions. Patented blinds have the same performance in clear sky, better performance in partly cloudy sky, and worse performance in cloudy sky compared to existing blinds. All three types of blind achieve better performance than minimum performance required by the standards in clear and partly cloudy sky. In cloudy sky conditions, only new blinds meet the requirements of the standards for the minimum lum-days/year. Cloudy sky drops values of lum-days/year for 60% for all three types of blind compared to their performance in clear and partly cloudy sky. New and patented blind performance is almost the same in clear and partly cloudy sky, while performance of existing blinds is slightly lower in partly cloudy than in clear sky.

Chart 4 in Figure 7 represents values of lum-days/year achieved at the point close to interior partition wall for the west-oriented blinds. New blinds have better performance in clear and partly cloudy sky conditions than the other two types of blind. New and existing blinds have the same performance in cloudy sky and better performance than patented blinds. Existing blinds give higher values of lum-days/year than patented blinds in all sky conditions. All three types of blind meet requirements of standards for minimum lum-days/year in clear and partly cloudy sky, while none of them meets requirements in cloudy sky. The highest values of lum-days/year are in partly cloudy sky for all three types of blind, while the lowest values are gained in cloudy sky.

Comparison between values of lum-days/year for south- and west-oriented blinds showed that:

- New blinds perform better for west orientation at the point close to the window in clear and partly cloudy sky. Performance is the same for both orientations in cloudy sky. At the point close to the interior wall, values of lum-days/year are higher in cloudy and partly cloudy sky for south-oriented blinds, while in clear sky west-oriented blinds achieve higher values than south-oriented blinds.
- Patented blinds perform slightly better in clear sky, significantly better in partly cloudy sky, and worse in cloudy sky at the point close to the window at the west orientation compared to south orientation. At the point close to the interior wall, patented blinds perform slightly better at the west-oriented façade compared to south-oriented façade.
- Existing blinds give higher values of lum-days/year for west orientation compared to south orientation at both measured points in the space in all sky conditions.

Comparison between values of lum-days/year for south orientation shows higher values at the point close to the window than at the point close to the interior wall for all three types of blind and in all sky conditions. For the west orientation the higher values are achieved at the points close to the window in clear and partly cloudy sky for all types of blind. In cloudy sky, new blinds have higher performance at the points close to the window, while patented and existing blinds show the same performance at both points.

Based on analysis of four charts in Figure 7, new blind application provides the highest values of lum-days/year compared to the other two blinds for both orientations, at both measured points, and in all sky conditions. New blinds meet requirements of the standards for minimum lum-days/year at the point close to the window for both orientations and all sky conditions. At the point close to the interior wall, new blinds do not meet minimum requirements of standards only in cloudy sky.

Based on the conclusion that new blinds show the best performance overall and for the most of the time meet requirements of the standards for both illuminance and luminance level in the space, the user of DMF can make the decision to chose new blinds to be applied at an office building in Roanoke, Virginia.

Limitations

This research focuses only on daylighting performance of the shading device, such as illuminance and luminance level in the space. Investigation of other performance requirements for shading device (thermal, control, cost, and aesthetic) will be the objective of future research.

The research is conducted only for:

- Office building that contains computers
- Venetian blinds
- One location in the USA (Roanoke, Virginia)
- Climate conditions on March 21, June 21, December 21
- Three times of the day – 11:00 a.m., 12:00 p.m., and 3:00 p.m. for south orientation and 12:00 a.m., 2:00 p.m., and 4:00 p.m. for west orientation

Development of the computer simulation tool for the decision-making process for the selection/design of the shading device based on its daylighting performance is the objective of future research.

Significance of Results

By developing the decision-making framework (DMF), appropriate selection and design of the shading device based on its daylighting performance is achieved, which leads to the best possible daylighting performance of the shading device as a part of the window segment.

The following research results are significant for future application in practice:

- DMF can guide architects and clients in selection of the most appropriate shading device for the specific building type and location, based on the daylighting performance of the shading device.
- DMF can guide the design of the new shading device system, taking into consideration its daylighting performance. In this way, daylighting performance of the shading device can be improved.
- DMF can be a basis for developing software for:
    - Selection of the best existing device among several alternatives that can be used for specific building and climate and site conditions
    - Selection of the best design among several design alternatives of the new shading device system

The software can be a helpful simulation tool in the conceptual as well as detail phase of the building design and, specifically, façade design.

CONCLUSIONS

The research described in this paper has the following objectives:

- To determine daylighting performance required for the shading device
- To define variables that affect shading device daylighting performance
- To develop a decision-making framework (DMF) that is used as an analysis tool in the process of selection and design of the shading device systems based on daylighting performance
- To validate DMF

The research determines variables that influence the shading device daylight performances and their relationships. Appropriate daylighting performance measures (such as illuminance and luminance level) are identified and their relationships with variables are described. Interactions among the variables and effects of these interactions on the daylighting performance are explained and quantified in the DMF.

This research investigates only daylighting performance of venetian blinds installed at the office building that contains computers.

The DMF is intended to be used by:

- Building designers in the process of selection of an existing shading device system for a specific building at the given location. DMF can help designers of the buildings, together with the clients, to select the most appropriate shading device based on the imposed daylighting criteria.
- Manufacturers of shading device systems in the process of the design of the new shading device. By developing the DMF, shading device designers are able to understand the shading device daylighting performance from their design-imposed criteria. By using DMF, daylighting performance of a newly designed shading device can be improved in the early design phase.

The DMF is guidance for both architects and manufacturers of the shading device that helps in appropriate selection, as well as design of the shading device, thus improving its daylighting performance.

The DMF developed in this research is the algorithm that can be used as a basis for developing a simulation tool for future research. This simulation tool would be used for selection of the best possible:

- Shading device among existing systems
- Shading device design among several new designs

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