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SCALE-MODEL AND SIMULATION-BASED ASSESSMENTS FOR DESIGN ALTERNATIVES OF DAYLIGHT REDIRECTING SYSTEMS IN A SIDE-LIGHTING EDUCATIONAL ROOM

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INTRODUCTION

Daylighting in buildings is considered both as beneficial for the energy efficiency of buildings and for occupants' well-being (Boyce et al., 2003; Linhart and Scartezzini, 2010; Scartezzini et al., 1997). Daylighting contributes to sustainable development by substituting use of electricity in buildings (Scartezzini et al., 1994). The spectral composition of daylight has positive effects on the circadian rhythm of people while carrying out their daily cycle of activities (Bellia et al., 2011). It provides a major support on physical performance, productivity and visual comfort within buildings (Scartezzini et al., 1993). As educational buildings are in use during the whole day for multiple occupancies, the above concerns have been valid significantly providing sufficient work-plane illuminance (Park and Athienitis, 2003). Additional concerns are to increase students' learning skills, concentration time and motivation while avoiding glare, uncontrolled sun penetration and lack of sun shadings (Bellia et al., 2013; Heschong, 2003; Heschong et al. 2002; Light.wissen 02, 2014; Tanner, 2000). So, the case study of this research has been chosen as a design room in a university so as to take attention of these considerations and relate them to recent innovative daylighting solutions as stated below.

Daylight redirection is a technique to both reduce excess daylight at the building perimeter and increase daylight availability in deeper zones of buildings. Typical light redirecting systems include light-shelves, redirecting light to the ceiling (Beltran et al., 1997) ; hollow light guides, often coupled to concentrator assemblies, transporting light over multiple specular bounces (Wittkopf, 2007) ; fixed and operated blinds, blocking or redirecting light (Koster, 1989) ; as well as refractive and diffractive components such as laser cut panels and prismatic structures (Edmonds, 1993; Greenup, 2004) . They have been assessed for their capability to increase daylight penetration into the deep spaces. One study showed that after application of anidolic systems in a given existing space, daylight

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factor increased by 33% to 41% (Kleindienst and Andersen, 2006) . Another study focused on achieving energy savings for artificial lighting with an anidolic integrated ceiling of more than 20% (Scartezzini and Courret, 2002; Wittkopf et al., 2006) A study on light tubes versus fiber optics combined with a solar dish, indicated that at higher solar altitudes light tube systems had better results since they capture both direct sun and diffuse skylight. However, solar tracking dish concentrator systems, having a constant effective aperture towards the sun were more beneficial at lower solar altitudes (Oh et al., 2013) . Despite these wide range of systems and recent studies based on ongoing research, there is still a need to widen the knowledge base on their relevance and implementations in different cases according to location, climate and geometry of any space.

In this context, testing and applicability of redirecting systems are the key points in studies mentioned above. The studies usually employ two main methods: scale models and computational simulation. Scale models are a means to develop and evaluate variants in architectural design. As a means to access daylighting performance, they require a high degree of accuracy and careful selection of materials to reflect the surfaces properties and geometric precision of the proposed design, as well as a known luminous environment (Bodart et al., 2007; Kesten et al., 2010; Thanachareonkit et al. 2005) . The main sources of experimental errors of scale models are due to correspondence of sky conditions and the surrounding buildings (Kesten et al., 2010) . Other sources of experimental errors are surface reflectance due to inappropriate materials used in models, and sensors' photometric properties. The use of scale models in the early stage of lighting design process was recommended as a direct approach to daylighting performance of a real building; since scale models mostly and exactly correspond to distribution of daylight in a real room (Bodart et al., 2007; Thanachareonkit et al. 2005) . Such features have triggered us for testing and applying procedures of redirecting systems in this study. We can get an immediate idea about the region/part of the space at where redirected light has reached; so scale modeling can become the easiest and practical way of understanding the daylight redirection behavior in a space. In this study, it would also be possible to examine the potential of scale models to show us the redirection of each trial system , allowing quick modifications.

Computational simulation, due to their capability of presenting visual scenes and their ability to predict results of various design alternatives in alternative conditions, has become the most common and preferred method for the analytical/experimental studies (Kim and Chung, 2011) . To support the use of daylight simulations by architects in their design process to evaluate daylight performance (Ibarra and Reinhart, 2013), the integration of simulation analyses of lighting and different facades into architectural education has been suggested in a study (Reinhart et al., 2013) . In daylighting studies, computational light simulation, typically being implemented either as ray-tracing or particle-tracing algorithms (Duin et al., 1993; Lightscape, 2001; Ward, 1994) , allows to assess a multitude of design variants as digital models under conditions set by the user (Reinhart and Fitz, 2006; Wienold, 2009) . The light simulation software Radiance is based on a hybrid backwards-tracing algorithm to efficiently perform daylight simulations in an architectural context, combining a deterministic, specular-indirect and direct pass with a stochastic, diffuse-indirect pass (Larson et al., 1998) . It has been validated both analytically and by comparison to measurements (Geisler and Dur, 2008; Maamari et al. 2006; Schregle and Wienold, 2004) To reduce the computational cost of daylight simulation in changing luminous environment, the daylight coefficient method de-couples the calculation of light transport within the model from the luminance distribution of the sky, allowing rapid computation monthly, daily or sub-hourly results (Laouadi et al., 2008; Tregenza and Waters, 1983) . The technique leads to annual simulations and subsequently to a new type of climate-based daylight performance metrics (Reinhart and Weissman, 2012) . As clearly understood, computational simulations provide us detailed analyses which correspond to the real situations with high accuracy, unlike scale models. So, Radiance has been chosen to lead monthly numerical and visual findings in this study.

The experimental study, here, aims to propose of design alternatives of daylight redirecting systems, which are light shelves with a ceiling system, light duct, horizontal blind and 15^0 blind, and analyses to compare their daylight performance in a large and deep design studio, located in Urla, Izmir. Methodology has a comprehensive approach combining practicality of scale models to determine initial designs of redirection systems and fine-tuning opportunity of computational light simulation to finalize decisions about optical properties of redirection materials and fine geometrical details of systems (angles, dimensions) and providing daylight performance estimates for a whole year. The current geometry of the room, which is a large and deep space, is taken as a baseline case for the scale-model construction. In the assessment phase, the east facing studio reoriented to south to get benefit from the most effective solar angles for İzmir (38^0 N 27^0 E) and to get the highest performance of redirecting systems. Our choices depend on systems' characterization of performing well in hot/ temperate climates and primarily using direct sunlight. The site location is on a lower altitude and is dominated by clear sky conditions. Higher sun altitudes are available in Izmir. Scale models let us know about daylight redirection behavior in the space and the immediate modification of redirection system designs. That process provides us immediate information visually and practically about how each design variant redirects daylight. Illuminance measurements are taken in the scale model to compare and support visual assessments through initial numerical findings. Computational simulations provide monthly results both for work-plane illuminance and luminance maps for all design variants. The simulations shall lead to an evaluation of proposed designs according to required minimum illuminance as well as the uniformity of illuminance distribution.

EXPERIMENTAL SET-UP

This section explains how the experimental study has been set up including the survey of physical attributes and geographic condition of the design studio in the first section. The demonstration of the scale model referring to related literature and decisions on its materials is stated in the following section. Subsequently, measurement strategy for illuminance readings together with characterizations of design variants is mentioned explicitly. The final section of the second part is composed of steps about daylight simulation with Radiance.

Survey of the Existing Design Studio

Location and Orientation:

The studio is located on the second floor of a university building on the Urla Campus of the İzmir Institute of Technology (IZTECH) **(Figure 1),**

Figure 1. Exterior and interior view of the design studio.

at geographical coordinates $26{,}6^0$ East, $38{,}3^0$ North and an altitude of approximately 80,00 m over sea-level. The building is located on a slope falling towards the Bay of İzmir in the north-east. The campus is about 50 km West of İzmir, the third-largest city of Turkey. The longer façade of the studio is oriented towards east (80˚ from north). The climate of İzmir is humid subtropical. In such climatic regions, shading devices and small openings are means to control sunlight and heat gains as well as to prevent glare. As the studio is on the second floor, there was no obstruction by any building or natural elements during the measurement phase.

Geometry and Surface Properties:

The geometry of the design studio was taken over from a previous study (Kazanasmaz and Fırat, 2014) The surface reflectance of existing studio was estimated due to their material definitions getting from the literature (**Table 1**). The measurement and calculation of these, afterwards, were achieved using both a photometer and a luminance meter according to the method used in another study (Park and Athienitis, 2003) ; and were determined according to the Lambertian reflectance formulation (1). Estimated and calculated values matched very close to each other, so, the former has become valid as in **Table 1**,

$$L = \frac{E \; x \; \rho}{\pi} \tag{1}$$

where L is Luminance, E is Illuminance, ϱ is reflectance of the surface.

					Existing studio	Scale model
room	length (m)	17.65	Ceiling	Gypsum board reflection R	0.80	0.86
	width	11.25	Walls	painted with light matt color close to white reflection R	0.60	0.88
	height (ceiling) (m)	3.20	Floor	white polished marble reflection R	0.65	0.89
	height (structure) (m)	4.00				
window	width (m)	2.00	glass	Transmittance T	0.75	--
	height (m)	2.00				
	sill height (m)	0.90				

Table 1. Dimensions and surface properties for existing design studio and scale model.

The materials used in scale model were chosen both to resemble the real surface appearance and to emphasize light redirection characterization; so higher reflectance values have been aimed. This was explained in detail in **Section 2.2.** The reflectance of model surfaces were measured and calculated as mentioned above and stated in **Table 1.** The transmittance of the window glazing was calculated as the ratio of two measurements using a luminance meter pointed at an exterior surface from behind and in front of the glazing (Erlalelitepe et al., 2011; Fontoynont, 1999) .

Scale Model

This section explains the development process of the scale model to get prepared for observation of possible daylight redirection behavior of redirecting systems. The following section, then, mentions the simulation model construction for getting detailed illuminance values and photorealistic visualizations. So, starting with the first phase, a scale model based on current condition of the existing room was built with exchangeable facade modules allowing to quickly replace fenestration systems and materials. It has the same orientation and environmental conditions due to its location nearby the actual building on a flat ground without any obstructions. The model was constructed from wood at a scale of 1:15, with inner surfaces covered by matt (walls) and glossy (floor) white paper (**Figure 2**) . The suspended ceiling was built with white foam sandwich cardboards. The scale is determined due to literature which states that 1/100-1/10 scaled models are useful “to study accurately diffuse and direct daylight penetration” and “to have highly detailed inside views” (Bodart et al. 2007). They are preferred for building performance studies, daylight penetration and its distribution inside the space and daylighting measurements. Detailed ones scaled 1/10-1/1 can be useful when daylighting devices cannot be reduced in scale (Bodart et al. 2007) .

Previously conducted studies on scale models show that the choice of material is the special concern in this study. Since light redirection methods depend on ceiling, light duct and blinds; in addition, awareness of ceiling material sensitivity was necessary for acquiring accurate predictions (Cannon-Brookes, 1997) . A study focused on discrepancies observed in scale models due to inaccurate internal surface materials. Both higher and lower reflectance values than actual ones were tested in two scale models (Thanachareonkit et al., 2005) . As the actual and model surface materials were mentioned in **Section 2.1.2** and **Table 1**, and there was an emphasis on light redirection, higher reflectance were preferred similarly for internal surfaces as in the previous study. To identify them, surface reflectance measurements were taken using a digital photometer and a luminance meter on-site. They ranged from 86% to 89% (**Table 1**). The parts were fixed by using glue, tapes and screws. The glazing of the test room was not modeled. Frame of the windows and other details were also disregarded for simplicity.

Field Measurements

After the model construction phase, measurements of horizontal illuminance on a grid of locations (CIBSE, 2002) in the scale model were taken on December 15, 2014 at 10:30 am under clear sky conditions on an open space in front of the building, ensuring almost identical sky conditions. Similar illuminance measurements were obtained on the desk height (80 cm.) in existing design studio, simultaneously, using a digital photometer with an attached silicon photo diode receptor head, whose measuring range is 0.01-299,900 lx.

On the other hand, measurements were taken using a digital photometer attached to one detector measuring the unobstructed illuminance on top and four detectors inside the model. Measurement points are shown in **Figure 3.** The detectors in the model were mounted in a row on a rail, providing quasi-simultaneous measurements of horizontal illuminance in each row. The height of the sensor corresponds to a height of 0.80m according to the scale of 1:15 (**Figure 2**).

Illuminance readings in the model were compared with field measurements. The coefficient of determination (R^2) value was 98% which meant that knowing the illuminance at a point by the model gives an almost 98% chance of predicting their values on the measurement. However, the illuminance values were greater than values in the actual room. High surface reflectance and excluding the glass material in the model for simplicity and applicability of the daylighting systems might cause that. As the aim of working with a scale model was to figure out the daylight redirection behavior of each design variant and to achieve their immediate modifications rather than quantitatively matching measurement or validating a model, expected discrepancies (Thanachareonkit et al., 2005) between the model and the real space were not further quantified.

Instead, the scale model of the current configuration of the room was taken as the baseline case. The model was located to the outside in identical orientation and outdoor conditions of the actual room, to be compared and tested under real sky conditions. To observe the performance of each system efficiently, scale model was oriented towards south as this direction gains benefit of direct sunlight more effectively in İzmir for a longer time period during a winter day than other directions. The simulation model was also oriented similarly with the model. We just only inspired from the geometry of existing situation for the base case; since, this room is a large space whose window height from floor is 2.9 m. although the depth is 11.20 m. which exceeds conventionally daylit perimeter zone (window height times 1.5- 4.5 m in this room). Daylight redirection systems can be applicable and their performance can be compared in such a room. Thus, four design variants were applied to the scale model (**Figure 4**) due to their known efficiency in locations of high altitude angles, and in collection of

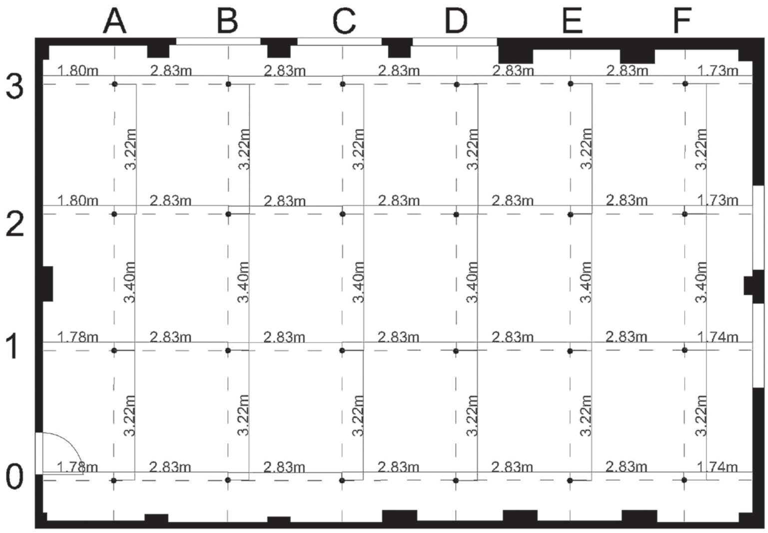


Figure 2. View from the inside of wooden scale model with four internal sensors mounted on a wooden bar sliding on rails.

Figure 3. Measurement points.

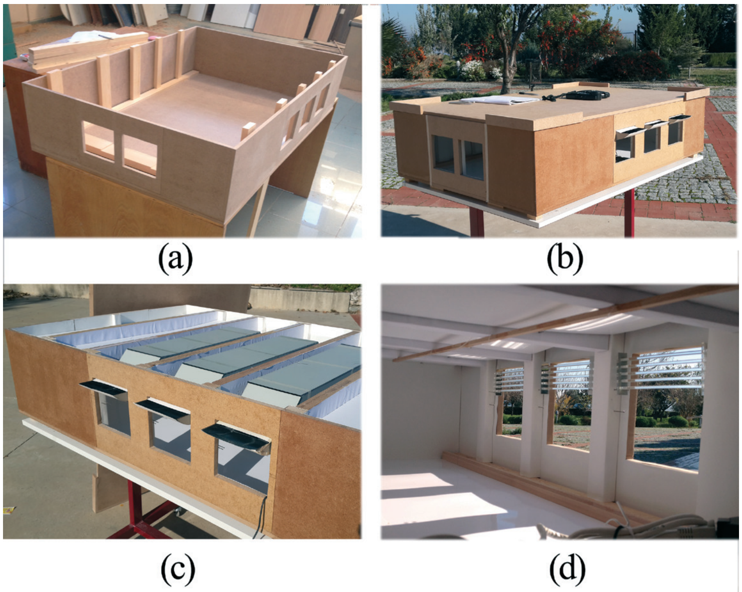


Figure 4. Wooden scale model (a) before covering of surfaces; (b) after construction and covered; (c) with the installation of light-ducts and uncovered; (d) with the installation of blinds and uncovered.

high zenithal sunlight, specifically for İzmir. The following section explains the design and characterization of each variant in detail.

Design Variants

Light Shelves with a Ceiling System:

Light shelves are installed on the inside of the south facade. The shelves are highly reflective mirrors, tilted towards the inside with a tilt angle of 11^0, to redirect daylight towards the center of the room. Specular ceiling panels reflect the light received from light shelves further to the back, bent downwards at varying angles to achieve reflection of light downwards at about 30^0 throughout a whole year. To avoid sharp patches of sun-light and to distribute light more equally, ceiling panels are manufactured from a highly reflective, but directionally scattering aluminum mirror.

Light-Ducts:

The geometry of an anidolic compound parabolic collector (Hess, 2007) is taken over from a previous study (Kleindienst and Andersen, 2006) . A collector, consisting of a parabolic concentrator, collects light entering the aperture within its acceptance angle, making optimized use of zenith light. A de-concentrator on the inside is limiting the beam width leaving the system. A light duct over the full width of the room is attached to the collector assembly. Due to the typical building structure, the light duct has to pass a beam and is then bent to the inner ceiling height. The scale model was made of highly reflective sheets and acrylic backside mirrors, relying on materials and techniques commonly applied in architectural practice.

Anidolic devices are mounted to the model facade on each of the three south-facing windows. According to the scale of the model, light ducts represent a length of 11.25 m. and the width, equal to width of the window, of 2.00 m. Three apertures are cut in the bottom of the light ducts. The first aperture represents a width of 0.72 m. The second one consists of two lined up apertures of the same width as the first one, the third aperture close to the inner wall represents a width of 1.72 m. **Figure 5** presents the section of this system and the apertures.

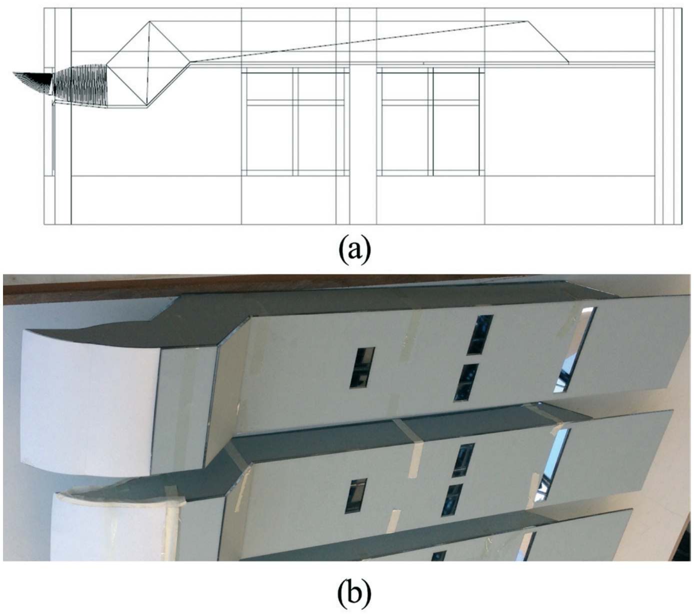


Figure 5. The light duct (a) the section, (b) the apertures below the duct.

Blinds, Horizontal and Tilted:

Three sets of blinds are mounted on the inside of the upper windows. The slats of the blinds are composed of highly reflective mirrors; the material is the same as used for the light shelves. In one variant, slats are positioned horizontally, in the second variant they are tilted towards inside with an angle of 15^0. The aim of the blinds is to reflect daylight to the back of the room and towards the ceiling, providing an even distribution of illuminance.

Each blind system in the scale model consists of 5 rectangular shaped slats, which are 120 mm. in length, 20 mm. depth. Their spacing is 20 mm. The blinds were modeled in CAD and laser-cut from acrylic mirror sheets to achieve a high degree of precision in the scale model. No additional reflective ceiling system was combined with the blinds.

Daylight Simulation with Radiance

As the scale model development with design variants have been completed, computational analysis becomes the subsequent process to get deep understanding of their performance over a year; and with fine detailed optical properties of redirecting material definitions using Radiance.

Physical Attributes of the Model

A model of the existing studio space was created using the open-source modeling software Blender (Hess, 2007; Welford and Winston, 1989) . Each proposed design variant was added to the model on a separate layer. Descriptive material names were chosen to allow mapping to material descriptions in subsequent simulations. The digital model was oriented so that the positive y-axis points North, using meters as units. The geometry was exported to the obj-format (Bourke, 2015) and then converted to a scene description for light simulation using the filter obj2rad, which is part of the Radiance distribution (Larson et al., 1998) .

Materials were defined according to names assigned to exported geometry, representing the observed and proposed materials for the base case and the design variants. The material definitions used in simulation are presented in **Table 1**. For calculation of daylight coefficients Radiance, sky and ground hemispheres were set to a uniform radiance of 1 W/m^2sr.

Simulation-Based Calculation of Daylight Coefficients

Daylight coefficients allow describing the energy transport between sky directions and sensors, independent from a particular sky radiance distribution. This allows de-coupling the simulation-step and its related computational cost from the amount of studied sky conditions. Sky coefficients were calculated in a first ray-tracing pass for a discrete set of sky-regions representing nearby directions, applying a coarse hemispherical subdivision set of 145 patches plus one single patch for reflected contributions from the ground (Welford and Winston, 1989) . The application of this coarse subdivision method is considered a valid simplification suitable for applications focusing at irradiance-based metrics; for detailed glare-studies a refined subdivision would be required.

Radiance supports the efficient calculation of daylight coefficient by the mean of ray contributions per given source. Two sensors were defined as views. One is set as a perspective camera (view type –vtv in Radiance), located close to the entrance to render photorealistic images providing a visual impression of the interior. The second, set as a parallel projection

```
vwrays −c 1024 −f f $ v i ewr e s −v f v f / i n s i d e . v f  | \
    rcontrib −n 8 −ab 3 −ad 8 −as 8 −c 1024 –ffc  \
    ‘ vwray s −d $viewres −vf vf / inside . vf ‘  \
    −f tregenza . cal −bn Ntbins −b tbin  \
    −o unf /${base}/ inside_r_%03d.unf  −m skyMat  \
    oct / ${base}.oct
```

Table 2. Calculation of daylight coefficients.

(view type –vtl) facing up, is used with the command vwrays to generate the positions and direction vectors for the ray-tracing tool rcontrib. This allows computation of luminance or illuminance daylight coefficients on a regular grid at any given resolution. The computation of the coefficients is implemented by the ray-tracer rtcontrib, which returns contributions to an imaging or integrating sensor signal either from surfaces identified by material or object names, or according to a functional definition of the subdivision method (tregenza.cal). The resulting daylight coefficients are recorded into separate files (**Table 2**).

The result is a set of 146 daylight coefficients for each sensor, each being a vector [x-resolution * y-resolution] of RGB-triplets stored in a high-dynamic-range image-format.

Generation of Irradiance and Radiance Maps According to Given Sky Conditions

To arrive at the particular sensor signal, or image in the case of imagine sensors, each daylight coefficients is multiplied with the average sky radiance of its corresponding patch, the products are summed up.

Using the Radiance command gensky, the radiance distribution of the sky dependent of direction, time, date and sky conditions (CIE clear sky) is generated. This continuous distribution is then translated into a discrete vector of sky-patch radiance averages using the command genskyvec. The patches match the subdivision method applied in the calculation of daylight coefficients. Multiplication and summation of the sky radiance vector and the daylight coefficients is implemented in the program dctimestep. The result is an image with pixel values presenting either irradiance or radiance (**Table 3**).

As this step of the calculation relies only on the multiplication and summation of vectors, the generation of results for changing times, dates and sky-conditions is computationally light-weight. While in climate-based daylight modeling, measured weather data at hourly or sub-hourly time-steps are considered, the comparative evaluation of designs in the scope of this work was focusing on clear sky conditions and based on monthly time-steps. For each month, a sky distribution according to the CIE clear sky model at 10:00 a.m. for Izmir, Turkey was considered. All proposed design alternatives assumed a permanent sun-shade for the lower windows to avoid visual discomfort.

```
gensky $month 21 10:00EET −o −26.7 −a 38.3 +s |  \
    genskyvec −m 1 | \
    dctimestep  unf /${base}/inside_r_%03d.unf  |  \
    pfilt > hdr /${base}_inside_r_${month}. hdr
```

Table 3. The corresponding average sky radiance.

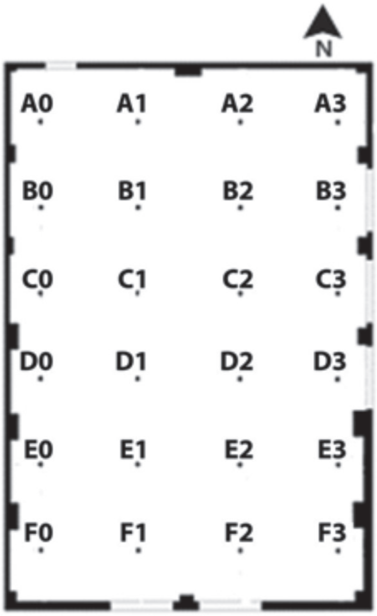


Figure 6. Point locations.

RESULTS

This section presents findings on horizontal illuminance in field measurements and scale model comparing the daylight distribution and explaining how design variants modified the existing daylight conditions. It provides us information about qualitative assessments on scale model, luminance distributions and illuminance values obtained from simulation calculations.

Illuminance in Field Measurements and Scale Model

Table 4 displays the illuminance values taken in the studio (lower rows) and in the scale model (upper rows) at points shown in **Figure 6.** As explained in **Section 2.3**, measurement readings are compatible with a 98% coefficient of determination; meaning that light distribution is similar; however, values in scale model are very higher than the ones in the studio. That depends on the high reflectance in the model without any glass material, and furniture in the real room.

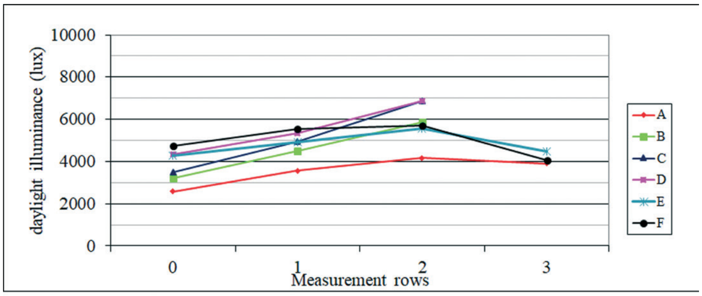
Figure 7 shows the daylight illuminance distribution for the baseline case and each design variants. As the sun patches occurred at points B3, C3 and D3 near the window, values of illuminance were excluded in the distribution graphs. The illuminance level ranged from 30,000 to 40,000 lux at these points.

The first row (Row 3) near the windows included sun patches in the baseline case. The second row (Row 2), which is at almost 3.7 m. distance from the windows, represents the highest daylight illuminance (almost 7000 lx at C2 and D2). Daylight dropped to approx. 25% at the center of Row 1 (B1-D1), which is at 7.1 m. distance from the windows. The situation was significantly different at other points, with almost 1% decrease in daylight illuminance near the wall sides. This is mainly due to the walls and side windows facing west. The decline at the center of Row 0 was nearly 20-30%, while this was 13-16% at the rest of the row. There was unbalanced distribution in the studio. Daylight illuminance ranged from 2500 lx to 4800 lx at the far end of the studio near the wall.

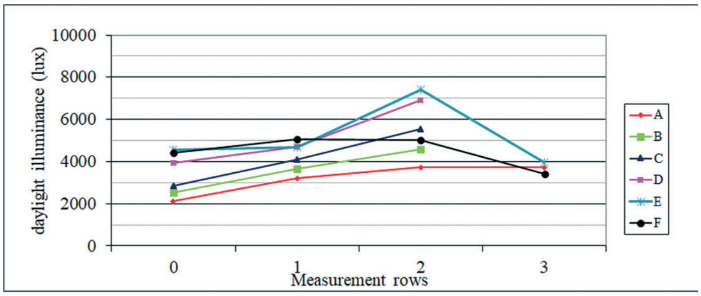
The application of light shelves with the ceiling system decreased daylight illuminance in the entire space in general. The decline varied between 21% and 25% at the center of Row 2, except the point E2. A very high illuminance was recorded at this point, with a sharp 36% increase rate. Illuminance varied from 2000 lx to 4500 lx in Row 0 and from 3200 lx to 5000 lx in Row 1, respectively. The installation of light ducts resulted in higher values of daylight illuminance near the side windows and lower

A0	120	**A1**	150	**A2**	250	**A3**	125
	2574		3570		4160		3900
B0	160	**B1**	290	**B2**	370	**B3**	1130
	3200		4510		5850		sun
C0	250	**C1**	530	**C2**	570	**C3**	1400
	3500		4950		6870		sun
D0	500	**D1**	960	**D2**	830	**D3**	1250
	4350		5350		6860		sun
E0	700	**E1**	2300	**E2**	2500	**E3**	850
	4270		4930		5560		4470
F0	950	**F1**	20000	**F2**	22000	**F3**	900
	4720		5560		5700		4070

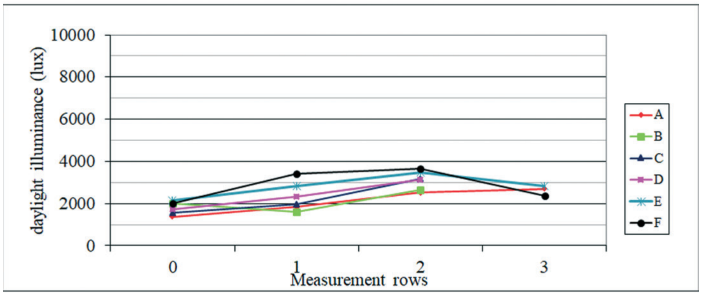
Table 4. Illuminance reading in the scale model (upper row) and the studio (lower row).



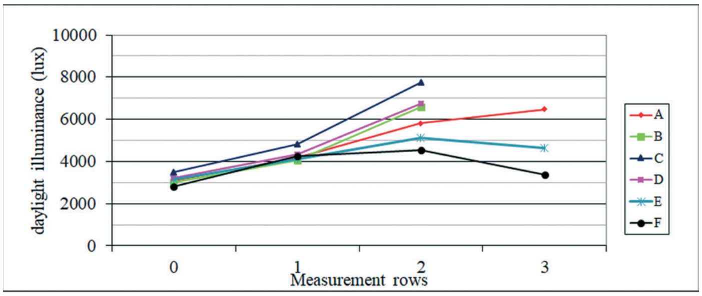
(a)



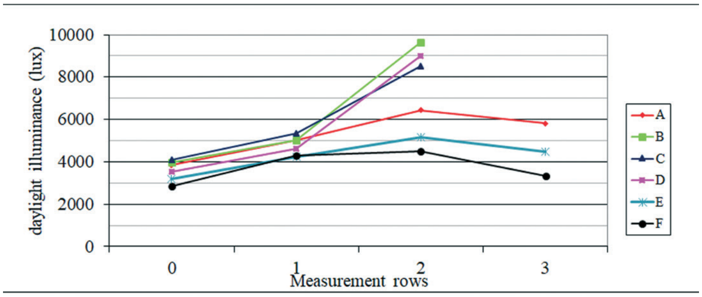
(b)



(c)



(d)



(e)

Figure 7. Daylight illuminance distribution (a) baseline; (b) light shelves with a ceiling system; (c) light duct; (d) blind, horizontal; (e) blind, 15^0.

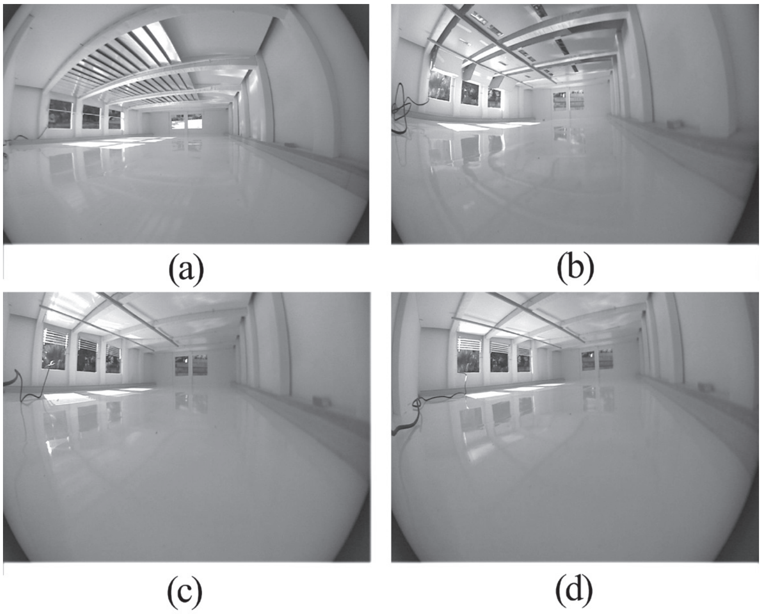


Figure 8. Views from the inside of the scale model (a) specular light shelves and ceiling system; (b) light duct; (c) blinds, horizontal; (d) blinds, 15^0 tilted.

values in the rest. Illuminance near the back walls varied from 1400 lx to 2100 lx, while it ranged from 1600 lx to 3400 lx in Row 1. The illuminance values at each point in the measurement grid were quite similar in both blind installations, with horizontal and tilted slats. A slight difference was observed in values in Row 2. Daylight was higher approximately 20% at the center of Row 2 with the tilted blinds than the horizontal ones.

Visual Assessments on Scale Model:

Figure 8 represents photographs taken inside the model with each variant. The scale model explored the comparison of the visual/qualitative assessments inside the studio achieved by each design variant. The longest sun patch was observed when light shelves with the ceiling system were installed. The numerical outcome supports this assessment as a means of getting the highest illuminance range of 5000-8000lx in the darkest region of the studio as shown **Figure 7b**. Sunlight was redirected from reflective surface of the shelf deep into the studio. Its trace was visible on the rear ceiling and wall surface (**Figure 8a**). Compared to the previous case, sun patch was shorter and light ducts caused darker area near the back walls (**Figure 8b**). Glistening areas were noticeable both on the floor and in the ceiling. The redirected sunlight from the horizontal reflective blinds to the ceiling covered a larger area than it was from tilted blinds (**Figure 8c-d**). However, they were composed of linear tracking patches rather than a full patch. This case resulted in a better-balanced distribution than the tilted case as figured out from the view. Though the smallest sun patch was observed in the case with tilted blinds, a gradual decrease of daylight's tracing on ceiling surface starting from the window to the back wall was noticeable in both situations. The scale model provided such visual assessments by monitoring with the non-instrumented eye. Sun patches destroyed uniform distribution of illuminance. They caused very bright areas such as in 15^0 blind system, very high illuminance was observed such as in B2, C2, D2 points, which varied between 8500-9500lx (**Figure7e**). Thus, an additional curtain with very low transmittance that was modelled in simulation runs to block the excessive light flux passing through the below windows.

Each design variant was removable and reusable in scale model. Removing and inserting design elements were handled easily. Light rays and movement of reflected light were monitored visually. It was practical to change slat angles, and to determine angles of the light duct in the beginning of design process by this application of the scale model. Evaluations and performance of each variant were perceived clearly from images and measured values. In addition, recorded measurements were in accordance with these qualitative assessments. Visual comparisons supported numerical values of illuminance. Thus, the model achieved the goal.

Calculations by Simulation

Findings were categorized according to the luminance distributions (**Figure 9-12**), illuminance maps (**Figure 13, 14**) and point illuminance (**Figure 15**). According to these, the illuminance ranged from 500 lx to 20000 lx near the windows (at 1-4 m. distance from the windows); 500 lx to 6000 lx at the center (at 4-6 m. distance from the windows); and 300 lx to 3000 lx near the back wall (at 6-10 m. distance from the windows) in the baseline model simulated for throughout the year. **Figure 15** also involves illuminance plots obtained on scale model to get an idea about comparisons with simulation findings. They are higher than the Radiance results.

When specular light shelves with a ceiling system was installed, illuminance ranged from 80 lx to 3000 lx in the windows; 100 lx to 2000 lx at the center; and 80 lx to 1000 lx near the back wall in winter months. Compared to the baseline case, significantly lower horizontal illuminance was calculated, since the additional low-transmittance-curtain mounted below the window blocked the disturbing excessive sunlight. This installation alone improved the uniformity. Comfortable and acceptable daylight illuminance was achieved at the center (representing C - E), while illuminance near the back of the studio and near the windows similarly met the required workplane illuminance in design studios of 500-750 lx. The area near the side wall represented the worst illuminance in all situations.

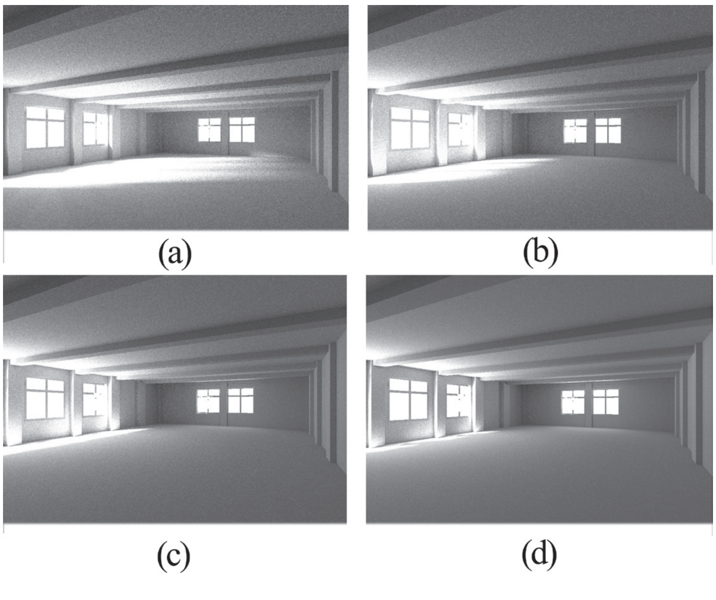


Figure 9. Luminance distribution for the baseline (a) January, December; (b) March, October; (c) April, September; (d) June, July.

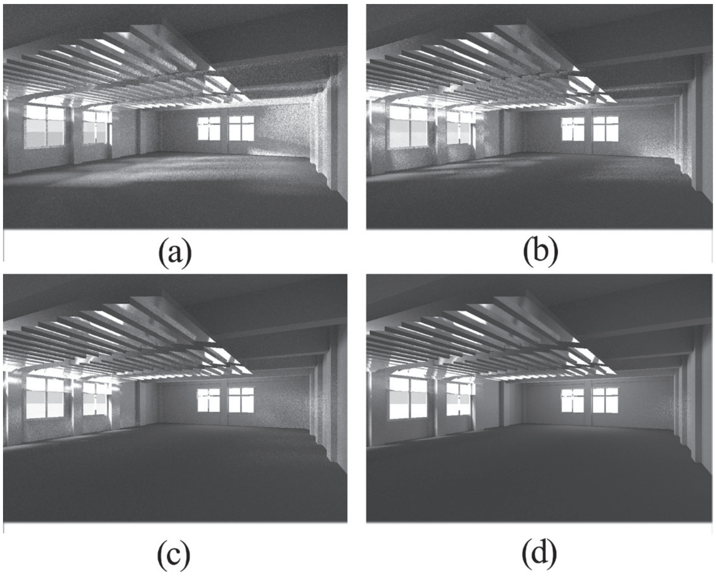


Figure 10. Luminance distribution for the light shelves (a) January, December; (b) March, October; (c) April, September; (d) June, July.

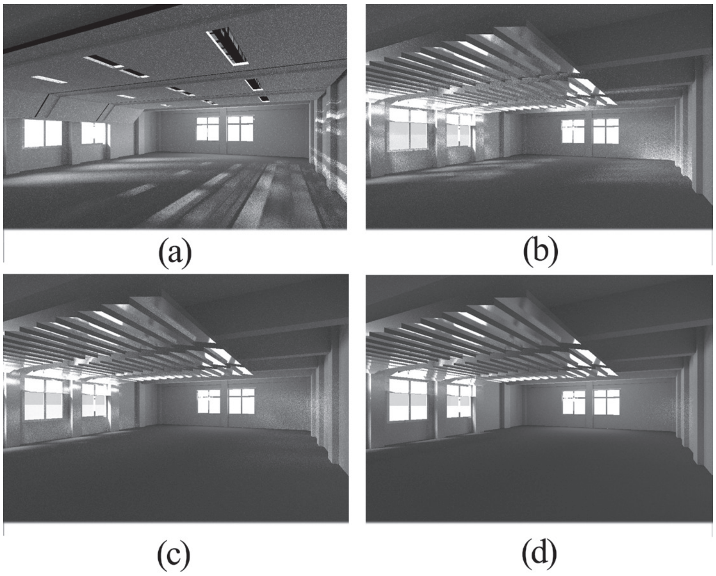


Figure 11. Luminance distribution for the light-ducts (a) January, December; (b) March, October; (c) April, September; (d) June, July.

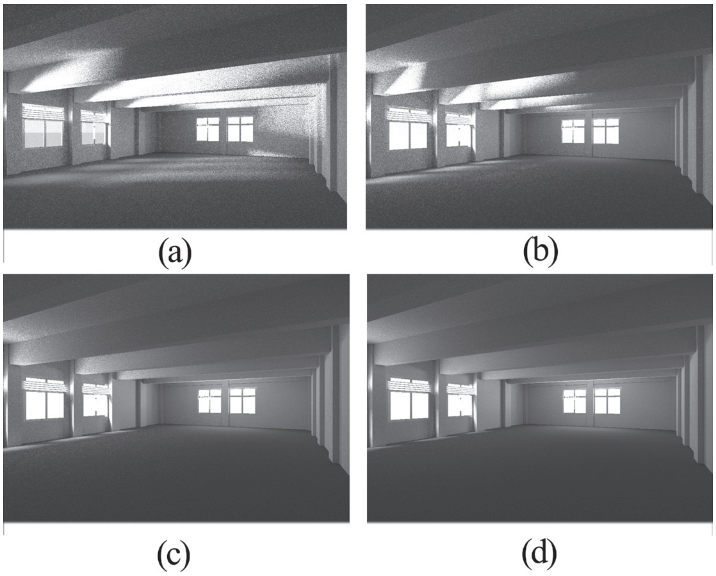


Figure 12. Luminance distribution for the blinds, 15^0 (a) January, December; (b) March, October; (c) April, September; (d) June, July.

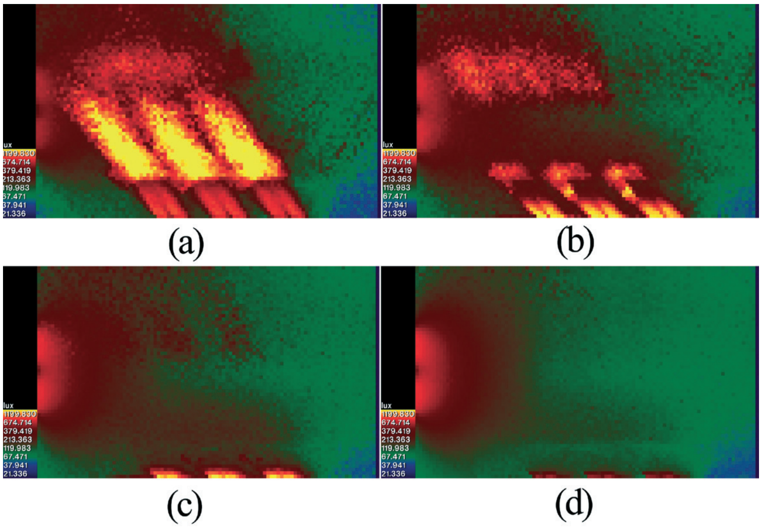


Figure 13. Illuminance maps for the light shelves (a) January, December; (b) February, November; (c) March, October; (d) April, September; (e) May, August; (f) June, July.

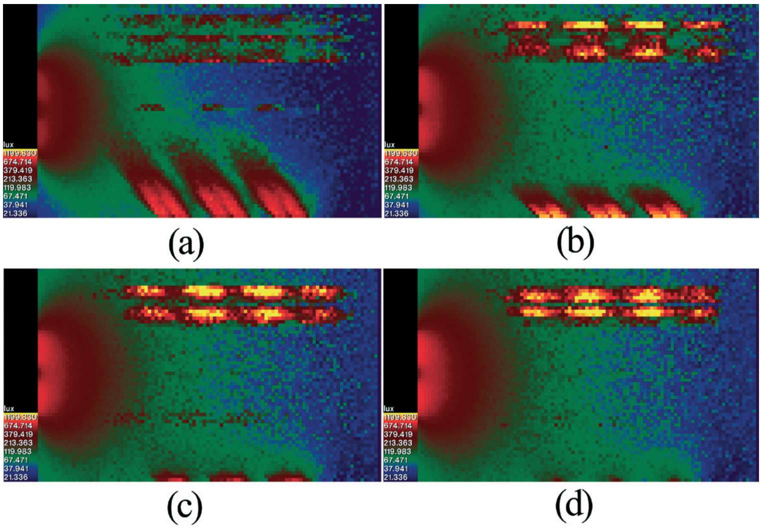


Figure 14. Illuminance maps for the light-ducts (a) January, December; (b) March, October; (c) April, September; (d) June, July.

When light-duct was installed, illuminance ranged from 40 lx to 800 lx near the windows; 400 lx to 500 lx at the center; and 40 lx to 500 lx near the back wall. Although daylight illuminance decreased to approx. 50% in the entire space in similar months, they provided nearly 1000 lx of illuminance near the back walls in equinoxes and summer months. This system failed to satisfy the required workplane illuminance in winter months.

When horizontal blinds were installed, the illuminance ranged from 100 lx to 1100 lx near the windows; 100 lx to 1000 lx at the center; and 80 lx to 900 lx near the wall. The range of daylight distribution at the center during winter months was higher than the ones in summer months. Light shelves with a ceiling system presented a very similar light distribution pattern as it was in the situation with horizontal blinds. Unlike the former, the middle zone is brighter in the latter by presenting higher daylight illuminances. On the other hand, the range of daylight illuminance near the walls during summer/equinox months was higher than the ones in winter months, when light ducts were in-use. At this situation, area near the windows was brighter in winter time. Light ducts acted reversely according to seasonal variations.

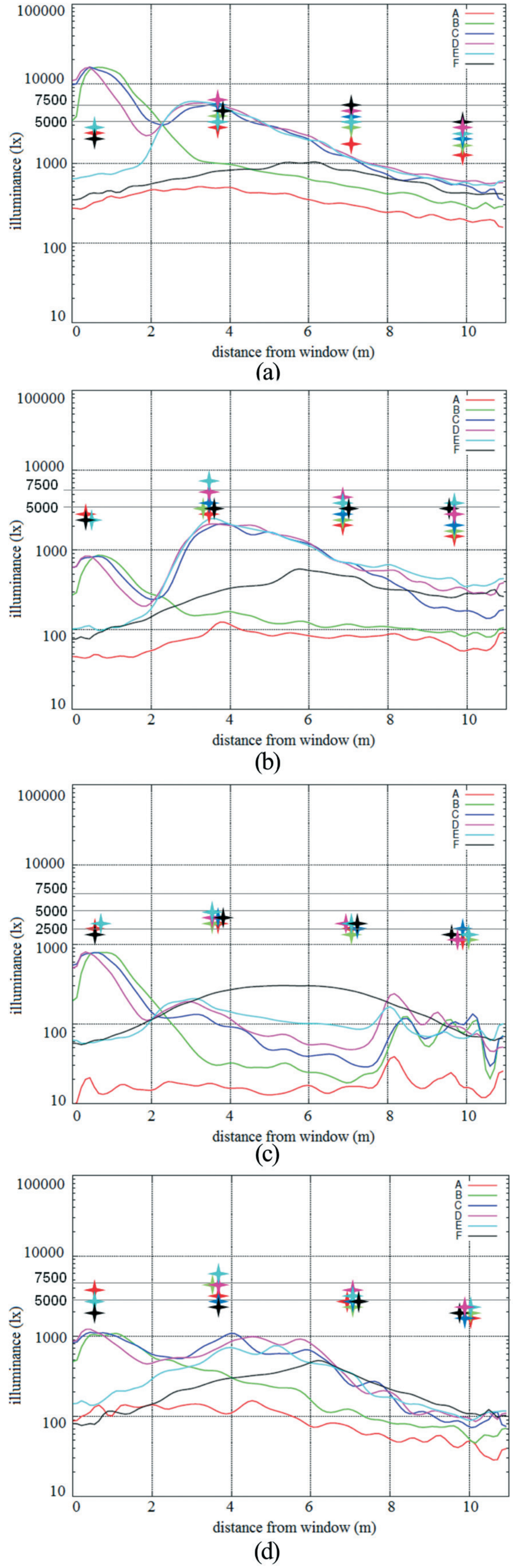


Figure 15. Illuminance for sensor rows depending on distance from window. (a) baseline (b) lightshelves (c) light ducts (d) blinds horizontal; and illuminance plots on the scale model.

DISCUSSION AND CONCLUSIONS

This study aimed to compare the performance of daylight redirecting systems; namely, light shelves with a ceiling system, light duct, horizontal blind and 15^0 blind, in a design studio in Urla, İzmir. Scale-model based analyses provided the opportunity to assess each system visually, meaning that, visual information about where the redirected light hits inside the room, where the sun patch occurs, or which region of the room is darker or brighter. Scaled systems could be quickly modified on the model and; following these basic observations, they could be compared while providing us an insight understanding of daylight redirection behavior inside the space. On the contrary, simulation based assessments revealed detailed illuminance distributions, numerical findings, and luminance maps, visual findings as the eye sees, for the whole year. Geometrical and optical characterization of the systems could be accurately determined. So, two types of assessment tools have become complementary phases used in this study to understand and illustrate the redirection behavior of each system.

Evaluations are explained as below by taking into consideration all findings together:

Regarding the Function of Space

As the function of space is for the educational purpose, the sufficient work-plane illuminance is required to be around 500 – 750 lx according to standards. Light shelves with a ceiling system is found to be the most successful implementation in terms of satisfying the high illuminance range in the entire room, uniformity and transporting daylight deep into the space, in equinox and winter period. These seasons are specific to function; since they cover active academic semesters when the space is fully used. Glare could be prevented and uniformity was satisfied using the 10% visible transmittance sun shade at the lower part of the window. Consequently, as visual comfort conditions could be achieved so far, light shelf design with a ceiling system can be chosen and proposed for future designs of such rooms.

Regarding Sunshading, Climate and Sun Angles

As observed in existing studio and measured both in the studio and on the model, predominantly clear sky conditions in Izmir imply a high occurrence of excessive illuminance through south-facing windows especially in winter. To maintain visual comfort, the transmission of direct sun light has to be controlled. One undesirable effect is that application of simple shading systems, such as fabrics or blinds, reduce the total flux provided by the windows; so, artificial lighting would become necessary to achieve minimum illuminance for detailed work distant to the windows, leading to an increase of electrical energy demand.

Aiming at redirecting light from the upper, unshaded window zone deep into the studio, and considering high frequency of clear sky conditions in Izmir, all proposed designs make use of specular reflectors. For low sun altitude angles, all designs partially compensate for the reduction of radiant flux by the shading of the lower window zones.

For higher sun angles, titled reflectors such as light-shelves (tilt angle 11^0) and tilted specular louvers (tilt angle 15^0) perform better than horizontal reflectors. These tend to redirect light to the ceiling close to the window, providing little to the deeper plan. Blinds alone contribute in winter months, while addition of an adapted specular ceiling shows contributions over an extended period unless May to August. All these open systems depend on sun azimuth being close to south, which is given in results but not the case over the full occupancy period from morning to late afternoon.

For summer months from May to August, only design based on light-ducts, transporting light concentrated by anidolic collectors over multiple bounces deep into the building, provide significantly to the illuminance distant from the windows. However, the contributed additional illuminance is limited to a very small area below the openings in the light duct. Further work is needed to develop a suitable extraction mechanism, distributing the transported radiant flux equally over a larger area at working plane level.

The application of light-ducts in a climate characterized by clear sky conditions and high sun elevation angles is promising, and has potential for further optimization of acceptance angle and extraction technologies. That characterization very well fits the location of İzmir. It performs better in summer and equinox periods. However, in this case, it failed to satisfy the required daylight conditions in the middle and rear part of the room in winter periods. A limitation for light duct systems is the required ceiling height and the need for large collectors protruding from the facade. Other redirecting systems (light shelves and blinds), lead to challenges in terms of appropriate redirection for low sun elevations and over extended daily occupancy times. Optimized ceiling systems seem to be a requirement if such systems shall perform well during summer months.

This study is specific to the location of İzmir. Any other locations at higher or lower latitudes would lead to differentiated findings in relation to sun angles and seasons.

Regarding the Assessment Tools

Consequently, scale model was useful in qualitative assessments of redirecting systems. Redirected light on the ceiling and back wall could be visible by eye in the model. Longest and shortest sun patches could be differentiated. So, this whole process may be integrated in daylighting design to decide on initial redirection design variants, then, to continue with the detailed/numerical simulation analysis. As a very recent version of Radiance was employed in this study, the whole findings contributed to the related literature due to this simulation tool's accuracy and capability of presenting daylight performance inside the buildings.

Limitations can arise from discussions about time period in which the study was conducted and due to geographic conditions. Field measurements and observations on scale model were under the sun and sky conditions in December. Certain differentiated performance of redirecting systems can be resulted for another location and for a longer time period. Seasonal influence then can be monitored in scale model. These would be basis for a further study to enhance such an approach developed in this study, including a whole analysis of a building façade with a variation of interior space depths.

To conclude at this point, nature of daylight provides various challenges when designing our buildings to meet illuminance requirements. Thus, professionals and researchers shall continue to find new ways to benefit from it efficiently by proposing design variants.

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SCALE-MODEL AND SIMULATION-BASED ASSESSMENTS FOR DESIGN ALTERNATIVES OF DAYLIGHT REDIRECTING SYSTEMS IN A SIDE-LIGHTING EDUCATIONAL ROOM

Daylight has been proven to have positive effects on well-being, comfort and performance of occupants in buildings; it specifically increases learning performance in educational buildings. Side-lighting from one direction leads to unbalanced and insufficient illuminance, especially in large and deep spaces. A design studio at the Izmir Institute of Technology (IZTECH) in Urla, Turkey, has been chosen as an example of a space in such a context. Its geometrical attributes has taken to be the baseline. First, four daylight redirecting systems are applied on its 1/15 scale model to understand and compare their redirection behavior visually. Second, measurements on the scale model are taken to compare the daylight illuminance distributions. Third, to assess the overall performance in the sunny climate, illuminance and luminance maps for photorealistic visualization are calculated in monthly steps over one year. For efficient calculation of the time-steps to be considered, the daylight coefficient method has been applied. Though light ducts are found to be effective for high sun angles, in summer and equinoxes; very low illuminance in entire space make them fail in winter. Light shelves are determined to be the most convenient ones for this space, since they provided sufficient, uniform and high illuminance in equinoxes and winter.

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Anahtar Sözcükler: Günışığı, yönlendirme, ölçekli maket, simülasyon

YAN AYDINLATMALI BIR EĞİTİM MEKANINDA GÜNIŞIĞI YÖNLENDİRME SİSTEMLERİ TASARIM ALTERNATİFLERİNİN ÖLÇEKLİ MAKET VE SİMÜLASYON TABANLI DEĞERLENDİRMELERİ

Gün ışığının, bina kullanıcılarının refahı, konforu ve performansı üzerinde pozitif etkisi olduğu kanıtlanmıştır. Günışığı, özellikle, eğitim yapılarında öğrenme performansını da artıran bir etmendir. Tek yönlü yan aydınlatma, özellikle geniş ve derin hacimlerde, aydınlık düzeyinin dengesiz ve yetersiz olmasına yol açar. Bu bağlamda, İzmir Yüksek Teknoloji Enstitüsü (İYTE)'nde (Urla-Türkiye) bir tasarım stüdyosu, örnek olarak seçilmiştir. Geometrik özellikleri temel alınmıştır. İlk olarak, dört farklı ışık yönlendirme sistemi, ışık yönlendirme davranışlarının görsel olarak anlaşılması ve birbirleriyle karşılaştırılması için, 1/15 ölçekli makette uygulanmıştır. İkinci olarak, günışığı aydınlık düzeyi dağılımlarını karşılaştırabilmek için makette ölçümler yapılmıştır. Üçüncü olarak, performansın güneşli bir iklimde değerlendirilmesi amacıyla, aydınlık düzeyi ve fotogerçekçi görselleştirme adına parıltı dağılımları, tüm yıl boyunca aylık olarak hesaplanmıştır. Verimliliklerin istenilen zamanlarda hesaplanabilmesi için günışığı katsayısı yöntemi uygulanmıştır. Güneş

açılarının yüksek olduğu durumlar için ışık bacalarının daha etkin olduğu bulunmuş; buna karşın, kışın tüm hacimdeki aydınlık düzeyi çok düşük olduğundan bu sistemler başarısız olmuştur. Işık rafları ise bu hacim için en uygun sistem olarak belirlenmiştir; çünkü bu sistemler, ekinoks ve yaz dönemlerinde aydınlık düzeyini yeterli bir şekilde, düzgün dağılımlı ve yüksek olarak sağlamıştır.

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