Light & Engineering
Vol. 22, No. 3, pp. 56-66, 2014

Svetotekhnika
No. 6, 2014

COMPARISON OF ADVANCED DAYLIGHTING SYSTEMS TO IMPROVE ILLUMINANCE AND UNIFORMITY THROUGH SIMULATION MODELLING

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ABSTRACT

Deficiencies in daylighting performance (illuminance and uniformity) of educational facilities may cause health problems, work performance loss and excessive energy consumption. The varying nature of daylight in daily and yearly basis is a strong challenge on that matter. Advanced daylighting systems have been developed to overcome this challenge. Improving the daylighting performance of existing buildings is another difficulty in daylighting design. Daylighting design needs should be carefully considered at the initial design stages of the buildings. So, the aim of this study was to improve the illuminance and uniformity in four selected architectural design studios in Izmir. Measurements of daylight illuminance were conducted in May and June 2012. Simulation models were built in Ecotect/Radiance. To reach the best daylighting performance, simulations were carried out by Desktop Radiance with applying laser cut panels, prismatic panels and light shelves. It is considered that retrofitting efforts after the construction would be inadequate regarding daylighting, unless complying with the standards during the design process.

Keywords: daylighting, uniformity, laser cut, prismatic, light shelf, simulation

1. INTRODUCTION

Architectural design students need to study in environments that have satisfying lighting performance. They need uniform and adequate illuminance levels to work on detailed drawings and models easily [1]. Since educational facilities are largely daytime occupied environments, enhancing daylighting performance of these spaces would reduce artificial lighting use and save electrical energy [2]. Technological developments led to advanced daylighting systems to improve the daylighting performance of the interiors. These systems obstruct direct sunlight to prevent glare, and/or transport daylight into deeper spaces away from daylighting apertures. Combination of system elements, application of new materials with optical properties, and their sizing possibilities led to design such systems continuously with a growing interest. There are many types of advanced systems as mentioned in literature. Some of them are light shelves, prismatic panels, laser cut panels, anidolic systems (ceilings, zenithal openings, solar blinds), holographic optical elements, scattering systems and light transporting systems (light pipes, solar tubes, heliostats) [3–6].

Several studies focused on their application in buildings and their impact on daylighting performance. Bleney and Edmonds [7] recommended using laser cut panels as light redirection systems only if they were designed with the combination of fixed shading devices in a school in Brisbane, Australia. Sweitzer [8] identified the critical impacts of prismatic panels on the reflections and shadows on interior surfaces in perimeter offices. They concluded similarly that these redirecting systems effectively altered the daylighting distribution only if the window aperture was set accordingly. A horizontal light pipe was integrated with laser cut panels to improve daylighting performance and uniformity of daylight distribution in a test room. This computational study concluded the successful illuminance enhancement inside the room [9].

Aghemo, Pellegrino and Lo Verso [10] compared the daylighting effects of overhangs, horizontal fins and external, internal and external/internal light shelves. It was observed that application of internal light shelves provided highest average illuminance between the systems under clear sky conditions; but reduced the uniformity and in summer, failed to provide adequate obstruction of the direct sunlight. Also, external light shelves provided a better daylight penetration and uniformity. Lim, Kandar, Ahmad and Ossen [11] recommended using internal/ external light shelves to improve the uniformity and lower the high working plane illuminance under tropical sky; and concluded that blinds should be integrated to the system in order to prevent glare.

One noteworthy aspect about related literature is that they extensively adopted the computer based simulations. When compared with scale models and analytical calculations, computer based simulation tools are less time consuming, easier to adapt to design changes and more flexible to conduct trials on different variables like materials, aperture sizes etc. Also users prefer using computer based daylighting simulation tools, which give reliable analysis results, have practical user-interface and provide self teaching materials and convenient databases [12,13].

Desktop Radiance is one of the commonly used tool, which works embedded in other tools such as AutoCAD, Ecotect and DesignBuilder. It is user friendly. It uses the CIE sky models (clear sky, intermediate sky, overcast sky and uniform sky) and runs analysis on single or grids of reference points and produces detailed renderings from which illuminance or luminance values of surfaces can be attained [14,15].

Several studies aim to validate Radiance simulations in case of various material combinations, under different sky conditions, while exposed to external obstructions or testing it among other tools [16–20]. Thanachareonkit, Scartezzini and Robinson [19] validated the modeling/ simulation techniques of Radiance for prismatic films and laser cut panels; while Reinhart and Andersen [20] concluded that Radiance was capable of modeling and make accurate calculations on translucent objects by using Radiance materials of *trans* and *transdata*.

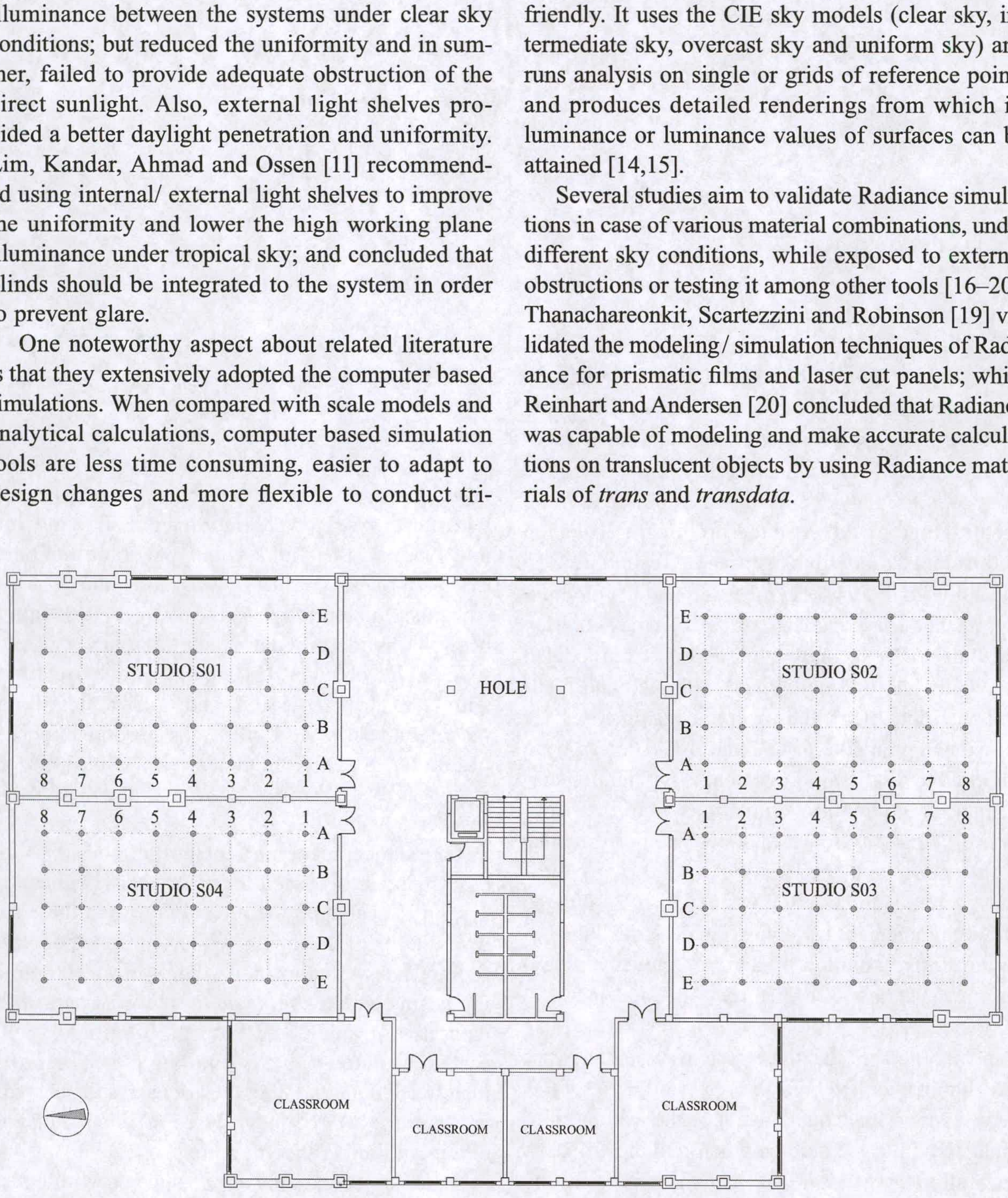


Fig. 1. General layout of the building and the measurement points

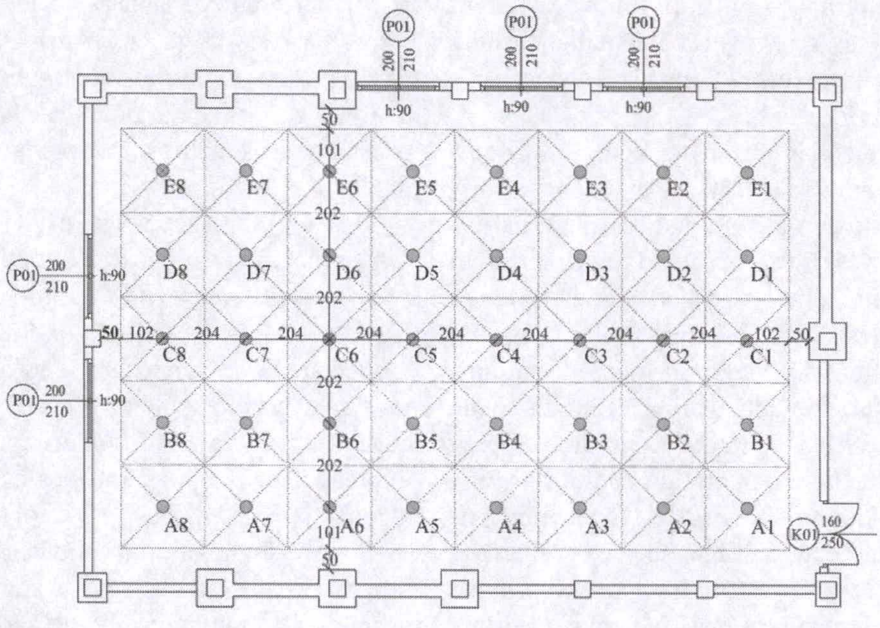


Fig. 2. The schematical expression and the measurement points of S01

In the view of these considerations, this paper presents the modeling of advanced daylighting systems to evaluate illuminance and uniformity in architectural design studios in Izmir Institute of Technology Faculty of Architecture. The purpose of this study was to analyze and improve the daylighting performance of the selected architectural design studios located in Izmir Institute of Technology. To reach this goal, first, field measurements of daylight illuminance was conducted on selected days in May and June 2012. Secondly, the studios were modeled in Ecotect and the model was calibrated and finalized regarding the field measurements. Finally, laser cut panels, prismatic panels and light shelves were proposed to test the improvement in daylighting performance. Daylighting simulations were then conducted using Desktop Radiance. The performance of the model and the existing daylighting conditions were quantitatively investigated and validated by measurements. The aim was to determine the optimum design solution by applying advanced daylighting systems with different size and material combinations.

It was expected that these systems would increase the illuminance levels in the rear wall area, which were severely inadequate, balance the average illuminance within the studios when moving from the rear wall to the window wall with the largest glazing area, and prevent existing sun patches due to their sun shading characteristics.

2. PHYSICAL FACILITY AND CLIMATIC CONDITIONS

The study was carried out in Izmir Institute of Technology Faculty of Architecture. The climate type of İzmir is humid subtropical, which is mild with no dry season, hot summer. Following July and August, the highest daily average temperatures are observed during May and June [21]. The sun position for the selected date for this study, May 4th, is identified with the azimuth and altitude angles obtained by Ecotect; which are 105.5^0 and 42.8^0 at 9:00; –150.2^0 and 64.5^0 at 13:00; and –97.6^0 and 34.7^0 at 16:00. Direct solar exposure (radiation) at 9:00, 13:00 and 16:00 may be obtained as 750 W/m^2, 845 W/m^2, and 360 W/m^2 respectively.

The subject matter is a total of four design studios, which are occupied for architectural education. They are located on the second floor of a three storey building of the faculty, which consisted of classrooms, design studios and laboratories. The building is situated on a hilly site in the west part of the campus (latitude 38° 19' north, longitude 26°37' east). Each storey of the building covers approximately 1600 m^2 and floor area of each subject studio is 198.5 m^2 (l: 17.65 m; w: 11.25 m). General layout of the building is shown in Fig. 1.

Four subject studios are designated with codes; namely, S01, S02, S03 and S04; facing north and east, south and east, south and west, north and west,

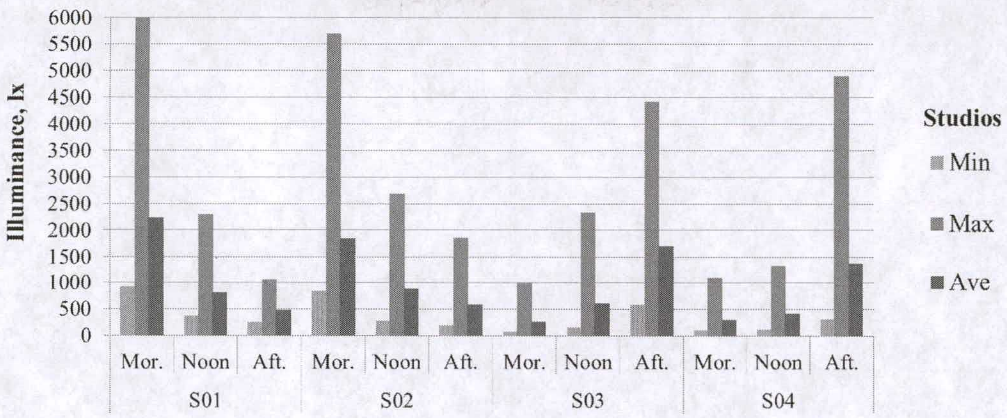


Fig. 3. Distribution of daylight illuminance on May 4th

respectively. Their story height is 3.20 m. The surface area of an identical double-glazed window in each studio is almost 4.00 m^2. The schematical expression of S01 is shown in Fig. 2. The window ratio (the window area / the floor area) is 11 % in S01 and S02, while it is 9 % in S03 and S04. There are two exterior walls at each studio.

3. PROCEDURE

3.1. Field Measurements of Daylight Illuminance and Uniformity

To evaluate the current daylighting performance of the studios, daylight illuminance was measured at specific points by following practical guidance offered by Chartered Institution of Building Services Engineers [CIBSE], (Fig. 2). Then, uniformity ratios were calculated. The uniformity is a measure of the balance of light intensity throughout the horizontal working area [22]. The number of measurement points and their locations were also determined according to the CIBSE Code 1994 [23]. Measurements were conducted using a digital luxmeter with a silicon photo diode detector in May and June 2012. It covered mainly clear sky conditions. Fig. 2 displays measurement points, which were located with equal spacing and 0.5 m away from walls / columns / partitions. The constant height for each reading was 0.8 m high from the floor level. In standards, the ratio of window area to external wall area is recommended as 35 % for rooms deeper than 14 m. And the ratio of window area to floor area is offered to be in range of 20 %-40 % [24]. The evaluation criteria for daylighting performance of the studios were determined regarding British Draft Development DD 73 and DIN 5034 [24, 25]. The optimum range of illuminance is 500–750 lx in drawing offices in educational buildings as described in the British standards [24]. DIN 5034 [25] stated the required uniformity values for the day lit interiors by the equations (1,2) below:

$$D_{min} / D_{max} > 0.67, \quad (1)$$

and

$$D_{min} / D_{ave} > 0.5. \quad (2)$$

3.2. Modelling in Ecotect / Radiance

In the second part of the study, studios were modelled in Autodesk Ecotect Analysis platform. Weather data and location information was uploaded to the program, RAL colour charts were used for defining the colour reflectance values of the materials. Ecotect models should be simple, without non-essential details for more accurate calculations [26]. Therefore, only the window openings and drawing tables were defined. Windows consisted of single glazing and white aluminium frame; and simple planes were modelled for the drawing tables (Fig. 2).

4. RESULTS

4.1. Findings Regarding Field Measurements

All measurements were conducted in four architectural design studios in the morning, at noon and in the afternoon in May and June, 2012. These two months were considered as worth to select, since it was possible to observe the highest impact of sunlight during the academic semester. However, the simulation model was set up for the days of May 4th and June 21st, 2012. Here, to show a part of noteworthy findings, only the ones obtained on May 4th

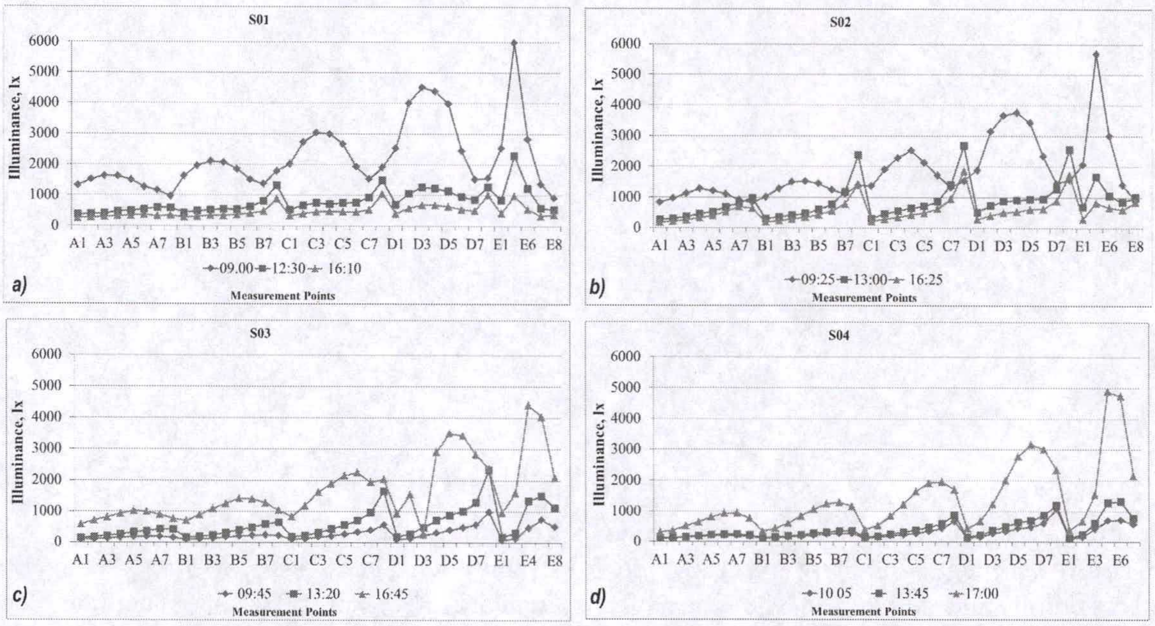


Fig. 4. Distribution of daylight illuminance at measurement points on May 4 th for (a) S01, (b) S02, (c) S03, (d) S04

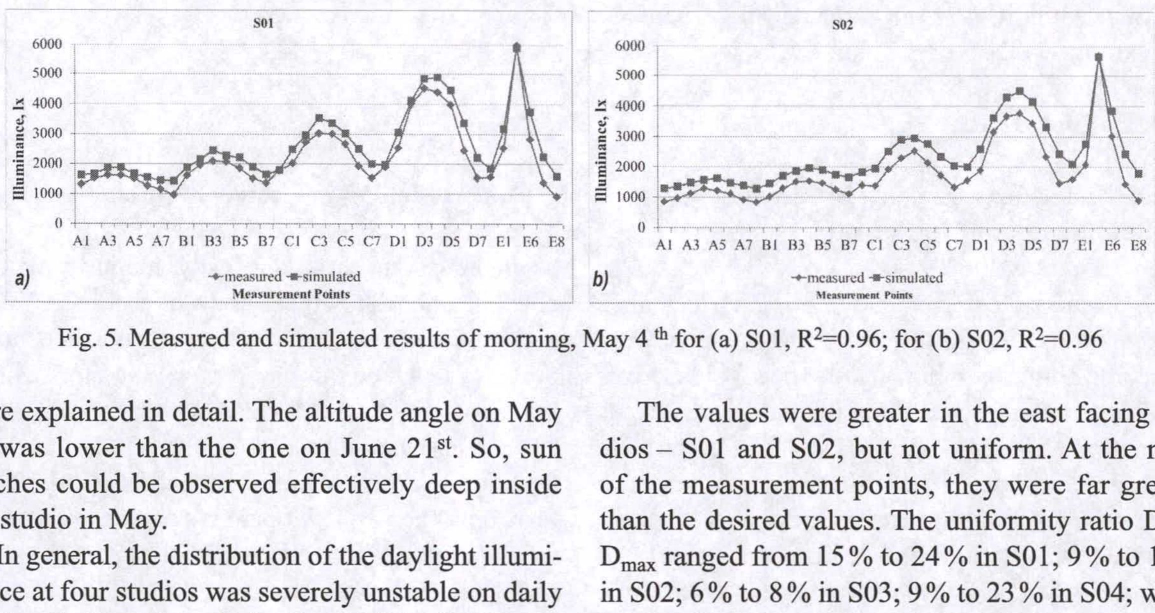


Fig. 5. Measured and simulated results of morning, May 4 th for (a) S01, R^2=0.96; for (b) S02, R^2=0.96

were explained in detail. The altitude angle on May 4th was lower than the one on June 21st. So, sun patches could be observed effectively deep inside the studio in May.

In general, the distribution of the daylight illuminance at four studios was severely unstable on daily and hourly basis (Fig. 3–4). The daylight distribution among the studios for the same time interval showed remarkable variations. Regarding the measurements in the morning, the daylight illumination in the west facing studios, S03 and S04, were seriously insufficient due to the daylighting requirements of a design studio in an educational building. For example, the daylight illuminance at more than 50 % of S03 was below 300 lx in the morning and below 500 lx at noon. Only 5 % floor area of the studio in the morning, 22.5 % at noon and 82.5 % in the afternoon had adequate daylight illuminance to satisfy the recommended illuminance of 750 lx. The average daylight illuminance was 266.68 lx at 09:45, 597.24 lx at 13:20 and 1700.52 lx at 16:45.

The values were greater in the east facing studios – S01 and S02, but not uniform. At the most of the measurement points, they were far greater than the desired values. The uniformity ratio D_{min}/D_{max} ranged from 15 % to 24 % in S01; 9 % to 15 % in S02; 6 % to 8 % in S03; 9 % to 23 % in S04; while uniformity ratio D_{min}/D_{ave} ranged from 41 % to 53 % in S01; 31 % to 45 % in S02; 15% to 29 % in S03 and 23 % to 31 % in S04. For example, in S01 the average illuminance continually increased regardless of time while approaching from row A towards row E, facing east. Sun patches were also observed in the morning at three measurement points; namely, E2, E3 and E5 in S01 and S02. They were just like glare sources in the afternoon at points, E4 and E7, in S03 and S04, as well.

Regarding the measurements at noon, the illuminance distribution showed similarities among these studios. According to the measurements in the afternoon, S01 and S02 showed a similar distribution, and had lower and more inadequate values than the

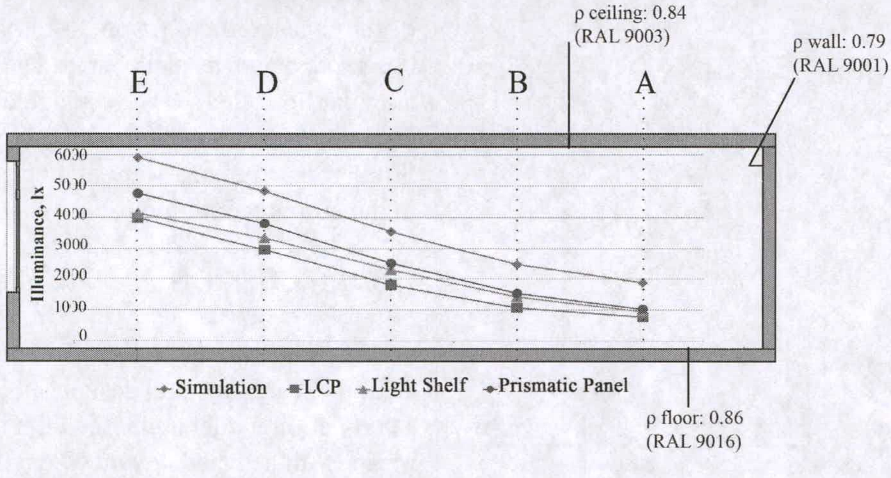


Fig. 6. Distribution of illuminance in the current situation and after the application of LCP, PP and LS

other studios had. The average illuminance in S03 and S04 was greater than the illuminance in S01 and S02, but severely non uniform and mostly far greater than the desired values (Figs. 3, 4).

4.2 Findings Regarding Radiance Simulations

Radiance outputs were compared with the field measurements to validate and finalize the Ecotect model. Regarding the validation process, the coefficient of determination (R^2) values ranged between 88 % and 98 % for all simulations on May 4th and between 78 % and 97 % on June 21st; showing the high accuracy of the simulation model. This meant that knowing the illuminance at a point by the simulation gives an almost (78–98) % chance of predicting their values on the measurement. Overall, the simulation outcomes fit the field measurements very well. Particularly, the simulation outputs were greater than the field measurements in all studios in the morning on May 4th. As a result of this confidence, thus, a laser-cut panel, a prismatic panel and a light shelf system were proposed and applied in Ecotect/Radiance model. Their effect on illuminance and uniformity were evaluated. Fig. 5 indicates the comparison of measured and simulated findings of the distribution of illuminance on May 4th, in S01 and S02.

4.3. Application of Proposed Daylighting Systems

Finally, advanced daylighting systems were proposed to improve the daylight illuminance and uniformity in these studios (Figs. 6, 7). In regard to the literature, these systems resemble the recent technical details and material applications; and have the ability of guiding/redirecting the daylight towards the low illuminated areas away from the window wall. These systems also may prevent the present sun patches and glare near the windows [7–11]. In this study, here, the laser cut panels, the prismatic panels and the light shelves were employed in daylighting simulations to comprehend their effects on the daylight illuminance and uniformity. The material characteristics (colour, reflectance and transmittance) and dimensions of these proposed daylighting systems were determined carefully in accordance to the previous studies [7–11]. Fig. 8 and Table 1 present the distribution of illuminance after the modeling of the laser cut panels, the prismatic panels and the light shelves. The uniformities ranged from 0.17 to 0.55. Tables 2–5 display an overview of findings and detailed assessments about the impact of each system on illuminance. The relation between the illuminance and floor area ratios were set up to understand the amount of floor area, which receives adequate illuminance/or not during the day.

Regarding the findings of laser-cut panels, the illuminance was lower at all measurement points, regardless of time, however, the illuminance distribution of the two rows closest to the rear wall, A and B, showed a more uniform distribution in the morning; and the illuminance was closer to the desired levels. But the distribution in the remaining area of the studio was not uniform. In addition, the sun patches were not observed at row E. There was not any improvement in daylighting conditions at noon and in the afternoon when compared with the previous condition.

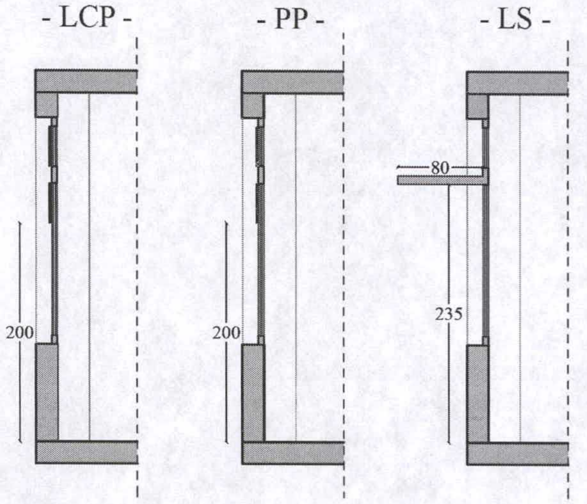


Fig. 7. Location of LCP, PP and LS

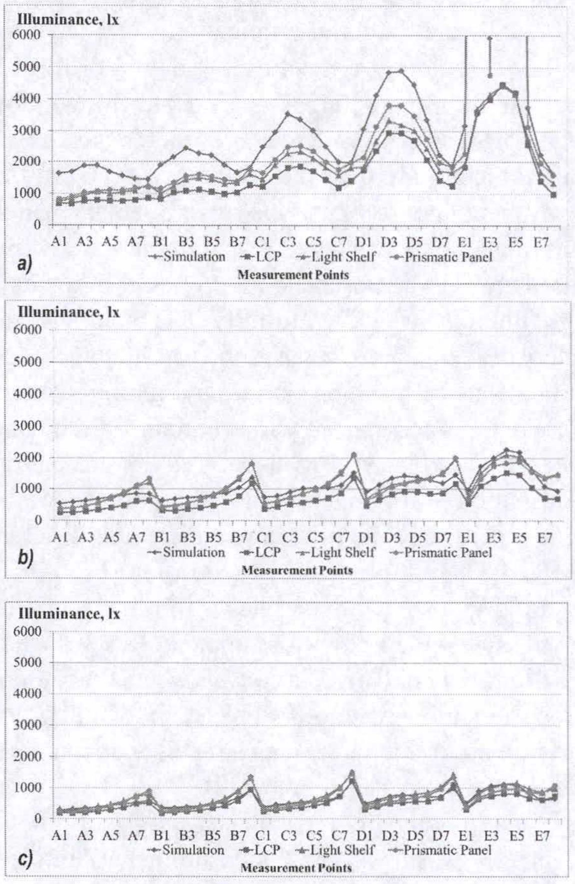


Fig. 8. Simulation results of the proposed systems on May 4th at; (a) 09:00, (b) 12:30, (c) 16:10 in S01

In the model, the prismatic panels were placed above eye level like the laser cut panels, 2 meters high from the floor, aiming to prevent glare that might have occurred by the redirection of daylight and not to block the outside view. The reflecting surfaces of the prismatic panels were determined as 45°. The illuminance in the prismatic panel equipped model was lower than the current condition at most of the measurement points. Sun patches were still observed, but on a smaller area. The 80 cm-wide rectangular light shelves were adopted in daylight simulations, because of their wider reflective surfaces. Similar distributions were attained when compared to the current condition.

6. DISCUSSION

This study aimed to find an optimum daylighting solution in architectural design studios by employing a simulation model under the light of field measurements with selected advanced daylighting systems; which were laser cut panels, prismatic panels and light shelves.

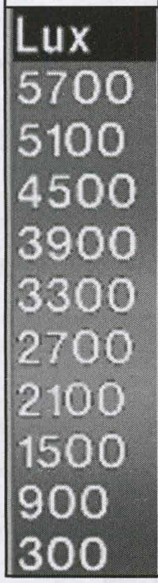
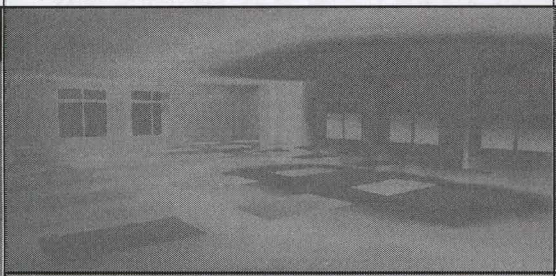
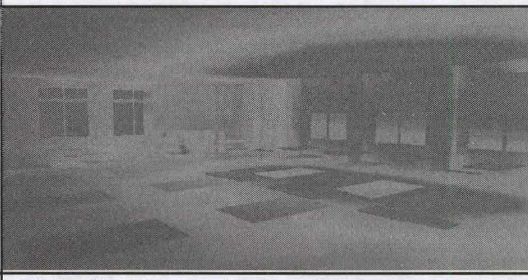
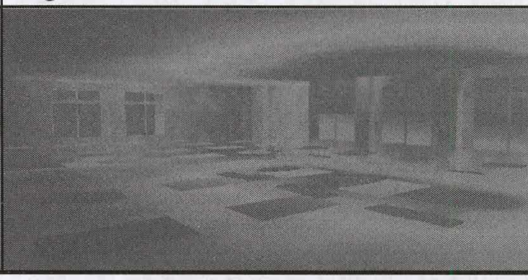
Discussions about several noteworthy findings of this study may guide further researchers and lighting designers in two ways, as iterated below.

a. First, Ecotect and Radiance are two simulation tools, which may be suggested to be used in daylighting performance studies together.

One noteworthy discussion may base on the physical correctness, usability and applicability of the computer based daylighting simulation tools. They have been the frequently-used and the mostly-reliable tools among the scale models and mathematical calculations in the prediction of illuminance and daylight factor in the field of daylighting design. Their priority depends on being less-time consuming, providing various visual scenes for various physical and sky conditions. It is possible to detect any deficiency in the design phase and provide solutions before its construction. Majority of the studies reviewed from literature concluded that Radiance is the most accurate tool among other tools and preferred to design and examine some technological components, i.e., laser-cut or prismatic panels in glazing [12,13,16–20].

So, the authors of this paper preferred to use Ecotect and Desktop Radiance to model the studios and to analyze their lighting condition. However, it was also understood from the literature that even the most precise tool might display misleading findings by the consideration of the various real sky conditions and a plenty of surface reflectance values. There are also evidences to support this statement in this study; i.e. there were several unbalanced illuminance variation between the measurements and the simulation model during the day, especially observed at the measurement points near the windows.

Table 1. Illuminance contour lines showing daylight distribution on May 4th, in the morning for S01

Scale	Current Condition	Prismatic Panel
		
	Laser Cut Panel	Light Shelf
		

It is expected that the development in simulation technologies would be enhanced with a growing acceleration. However, the noteworthy point here is which tool is the most accurate one at the moment and whether its accuracy/or inaccuracy depends on factors such as sky model, material, etc. The answers would allow the improvement in the simulation technology. Designers and researchers also would use such tools with an absolute awareness.

b. Second, the simulation results indicated that none of the applied daylighting systems satisfactorily improved the illuminance and daylight uniformity in the architectural design studios.

Another discussion may be stated here about the impact of daylighting systems on the parameters of daylighting performance, namely, the illuminance and uniformity. It was predicted that applied systems would illuminate the areas near the wall due to their light guiding characteristics. However, the prevented excessive light intensity by laser cut panels reduced the horizontal illuminance. For example, laser cut panels reduced the horizontal illuminance on the working surface near the window from about 39 klx to about 3 klx. Although they were successful in avoiding sun patches, they were unable to enhance the uniformity ratios up to the recommended

Table 2. Overview of the simulation results for the current condition on May 4th

May 4th	Illuminance (lx)	Floor Area Ratios (%)			Assessments
		Simulation			
		Morning	Noon	Afternoon	
S01	< 500	0	0	40	Excessive illuminance levels during morning.
	500 - 1000	0	50	50	Half of the floor area is overly illuminated at noon.
	> 1000	100	50	10	Severely unstable illuminance distribution in the afternoon.
S02	< 500	0	7.5	25	Similar illuminance distribution with S01.
	500 - 1000	0	35	35	Lesser floor area meets the desired illuminance levels at noon and in the afternoon.
	> 1000	100	57.5	40	
S03	< 500	80	45	2.5	Severely insufficient illuminance during morning at more than 3/4 of the floor area. In the afternoon, half of the measurement points are overly illuminated. Unstable illuminance distribution on hourly basis.
	500 - 1000	17.5	30	47.5	
	> 1000	2.5	25	50	
S04	< 500	75	62.5	0	Extreme changes in illuminance on hourly basis.
	500 - 1000	25	25	15	75% of the floor area is low illuminated in the morning, 85% of the floor area is overly illuminated in the afternoon.
	> 1000	0	12.5	85	

Table 3. Overview of the simulation results with LCP on May 4th

May 4th	Illuminance (lx)	Floor Area Ratios (%) Laser Cut Panel			Assessments
		Morning	Noon	Afternoon	
S01	< 500	0	35	55	In the morning, 27,5% of the floor area reached the desired illuminance.
	500 - 1000	27.5	45	40	At noon and in the afternoon, overly illuminated areas decreased while there has been a remarkable increase in the low illuminated areas.
	> 1000	72.5	20	5	
S02	< 500	0	32.5	45	Again, similar distribution with S01.
	500 - 1000	27.5	27.5	40	While the overly illuminated areas decreased, the illuminance levels fell below the required norms at noon and in the afternoon.
	> 1000	72.5	40	15	
S03	< 500	87.5	65	37.5	While there has been a decrease in overly illuminated areas after the panels were applied, also the low illuminated floor area increased, causing a severe deficiency in the daylighting conditions.
	500 - 1000	12.5	22.5	30	
	> 1000	0	12.5	32.5	
S04	< 500	82.5	77.5	27.5	Similar distribution with S03.
	500 - 1000	17.5	22.5	30	The panels acted as a shading device and lowered the illuminance throughout the studio.
	> 1000	0	0	42.5	

Table 4. Overview of the simulation results with prismatic panels on May 4th

May 4th	Illuminance (lx)	Floor Area Ratios (%) Prismatic Panel			Assessments
		Morning	Noon	Afternoon	
S01	< 500	0	12.5	42.5	Prismatic panels did not cause remarkable changes in illuminance distribution in the morning and in the afternoon.
	500 - 1000	5	35	47.5	
	> 1000	95	52.5	10	At noon, the panels worsened the daylighting conditions remarkably.
S02	< 500	0	27.5	45	In the morning, the panels provided adequate illumination to 20% of the floor area, while at noon and in the afternoon caused an increase in the low illuminated areas.
	500 - 1000	20	32.5	37.5	
	> 1000	80	40	17.5	
S03	< 500	85	60	17.5	The panels increased the amount of low illuminated areas while did not provide much improvement in the areas exposed to high levels of illumination.
	500 - 1000	15	25	32.5	
	> 1000	0	15	50	
S04	< 500	62.5	55	7.5	The panels increased the amount of floor area that meet the desired illuminance during the day, but also increased the low illuminated areas at noon and in the afternoon.
	500 - 1000	35	32.5	30	
	> 1000	2.5	12.5	62.5	

values. Thus, the systems only reduced the horizontal illuminance in general. Although the prismatic panels did not provide adequate sun shading for the areas, which were overly illuminated, others in general, showed sun shading characteristics rather than acting as light guiding elements.

The studies about the daylighting performance of laser cut and prismatic panels were mostly included rooms whose depths were almost 5–6 m [7–11]. However, the horizontal depth of the architectural studios in this study was 11.25 m. Also, the glazing ratio, as well as the number of glazed facades, was inadequate in such a space of this large amount of floor area. All of these considerations might be the cause of the inadequacy of these proposed and modeled daylighting systems. Also, all of these conditions were the results of unsolved design problems at the preliminary stages of the architectural design of the studios. One other reason might be in relation to the sun angles. These systems might be more effective in buildings located in high latitudes than the ones in İzmir.

7. CONCLUSION

Findings of this study can be summarized as:

- The 20 % of the floor area did not receive enough daylight in the morning period; and almost

Table 5. Overview of the simulation results with light shelves on May 4th

May 4th	Illuminance (lx)	Floor Area Ratios (%) Light Shelf			Assessments
		Morning	Noon	Afternoon	
S01	< 500	0	12.5	35	In the morning, provided adequate illumination to 12.5% of the floor area, but the laser cut panels had a better performance. At noon and in the afternoon, worsened the distribution.
	500 - 1000	12.5	37.5	45	
	> 1000	87.5	50	20	
S02	< 500	0	17.5	37.5	In the morning, provided adequate illumination to 1/4 of the floor area, but laser cut panels had a better performance. Distribution was similar with S01.
	500 - 1000	25	32.5	32.5	
	> 1000	75	50	30	
S03	< 500	77.5	55	25	In the morning, light shelves provided the best performance. At noon and in the afternoon, they decreased the uniformity and lowered the illuminance throughout the studio.
	500 - 1000	22.5	22.5	37.5	
	> 1000	0	22.5	37.5	
S04	< 500	62.5	50	15	The light shelves increased the amount of floor area exposed to adequate levels of illumination throughout the day, but also increased the overly illuminated areas in the morning and at noon, while increased the low illuminated areas in the afternoon.
	500 - 1000	35	30	35	
	> 1000	2.5	20	50	

60 % of the floor area was gloomy at noon (daytime) for the studios facing east. The existing daylighting conditions did not satisfy the uniformity rates.

• By applying laser-cut panels, prismatic panels and light shelves, trial simulation models displayed that uniformity values wouldn't be improved, although illuminance near the windows decreased sharply.

• All three of the systems showed sun shading characteristics rather than acting as light guiding elements.

• Retrofitting efforts to improve the daylighting conditions of existing buildings might become an ineffective and inefficient task. Designers and professionals should pay attention to apply requirements mentioned in the standards/or norms about daylighting at the design stage.

• Ecotect/Radiance modeling was a suitable tool to evaluate and retrofit an existing building's daylighting performance.

• Finally, daylighting decisions should be integrated with the building design in the preliminary design stages, since the main design decisions like glazing ratio, the number and positioning of the daylight apertures have remarkable effects on the daylighting performance of the buildings.

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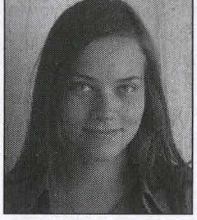

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