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Designing a dynamic fenestration to improve visual performance in educational spaces using daylight

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ABSTRACT

This research studies the daylighting performance of diverse design prototypes of a classroom unit. The prototypes are suggested for high-performance approach that reflects a dynamic design, through the incorporation of daylight that will boost up the learning experience. Simulation is carried out using Radiance and Daysim for daylighting measurements and Evalglare for glare analysis. Window to Wall Ratio (WWR) and window-sill height are designed to provide the optimum daylight levels for students performing different educational tasks. These two variables are evaluated according to certain goals and within certain constraints to refine the optimum solution. The result of this research is a design of dynamic façade that opens and shuts in response to the illumination levels required by the task performed; such as traditional learning, discussion or computer activities. The function of the dynamic façade is to achieve uniform and sufficient daylight in the classroom to perform visual tasks with minimal discomfort caused by the glare.

Keywords: daylighting, visual comfort, classroom design, dynamic façade, WWR, window-sill height

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1. Introduction

Throughout the architectural design of educational spaces, Indoor Environmental Quality (IEQ) has always been a vital aspect that must be utilized efficiently; as it is a crucial component of design. Sustaining adequate IEQ in schools has a great impact on the overall performance and productivity of the learning process inside the classroom. Visual comfort, which is one of the IEQ pillars, has been regarded as one of the most important environmental qualities in schools; providing the optimum lighting conditions and creating visually comfortable spaces for both students and teachers.Visual comfort can be acquired by daylighting or artificial lighting [1-3] Improving daylight provision in educational spaces is desirable for that it improves the feeling of health, wellbeing, alertness, it maintains the visual comfort, and it minimizes the electric lighting demands. However, if visual discomfort occurs, these benefits are likely to be negated. Achieving the required illuminance for each activity is important in creating a productive learning environment, hence, controlled illumination is another critical component in the design of the learning environments. Inadequate lighting controls may affect negatively, by producing glare, causing discomfort and poor performance [4-6]. A study by indicated that maintaining good lighting conditions in classrooms is a hard mission, as a variety of complex activities are performed within the same space, looking at the board, communication between students, teachers, and using technological tools such as laptops and notepads. Each task of the aforementioned requires different lighting conditions. Achieving appropriate lighting conditions depends on many parameters of design, such as space shape and size, ceiling height, internal reflectance's, shape, and size of the glazed area. A study by [7, 8] optimized the form of the classroom that provides the best daylight illuminance. The study found that the optimum layout is a rectangular ground plan with dimensions equal to 8.4m wide and 7.2m deep. The classroom height is usually determined in response to acoustics and reverberation control. and studied the classroom height in them researches, and found that classrooms with ceiling height more than 3.8m needs sound insulation. Fenestration design is one of the most important factors to consider while designing daylit spaces. Direct sunlight penetration into classrooms produces an unpleasant glare on the work surfaces, such as computer screens, making it difficult to learn. However, proper orientation of windows allows direct and diffused daylight to enter the space, and controls the glare formation. The selection and placement of windows should be determined by the amount of light needed, and based on the climatic conditions and the architectural design. On the other hand, window design involves multiple interconnected parameters such as the window–wall ratio (WWR), glazing type, and window-sill height [9-11].The main aim of the study is to achieve a flexible and dynamic fenestration design, in which daylight can be used for most of the occupancy times of classrooms. This dynamic design is used to improve the daylight performance as a criterion of the model classroom, where different learning activities take places, such as discussions, traditional learning, and computer use. The research suggests nine prototypes with different window-sill heights and WWRs. The prototypes are evaluated using computer simulation[12-17].

2. Case study description

The classroom used in this study is an example of the typical classrooms built in Amman, Jordan. The classroom unit has a total capacity of 30 students, with a floor area of 60m². The classroom dimensions are 8.40m long and 7.20m wide, with a clear height of 3.8m. All the suggested prototypes of the classroom face north. The most important quality of materials in lighting design is their reflectance. The reflectance of classroom materials used in this study is obtained from measurements taken in various existing classrooms in Amman. Fig.1 shows the geometry of the case study as well as the reflectance of its components.

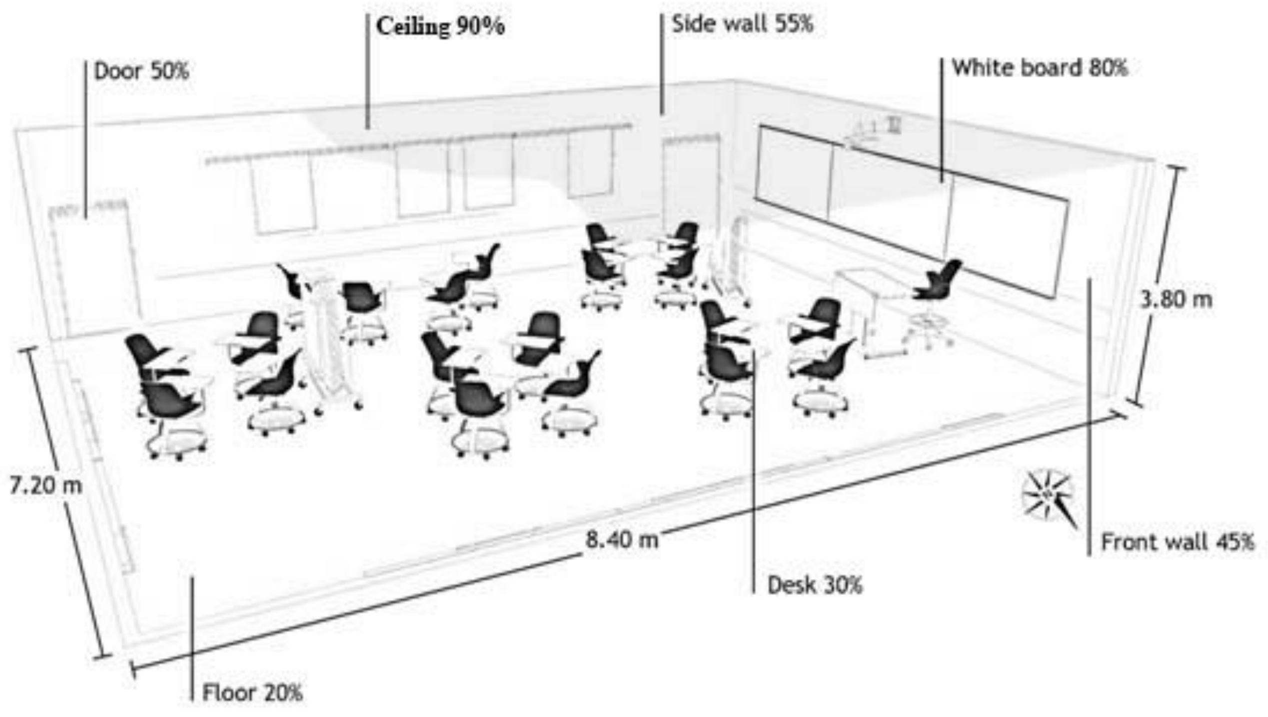

Figure1. The geometry of the case study

The suggested prototypes involve specific teaching activities; traditional teaching, computer use, and discussions. Each prototype is evaluated in response to the requirements of each activity or task. Figure 2 illustrates the arrangement differences of the classroom according to the activity taking place there, while Figure 3 shows a section of the suggested classroom.

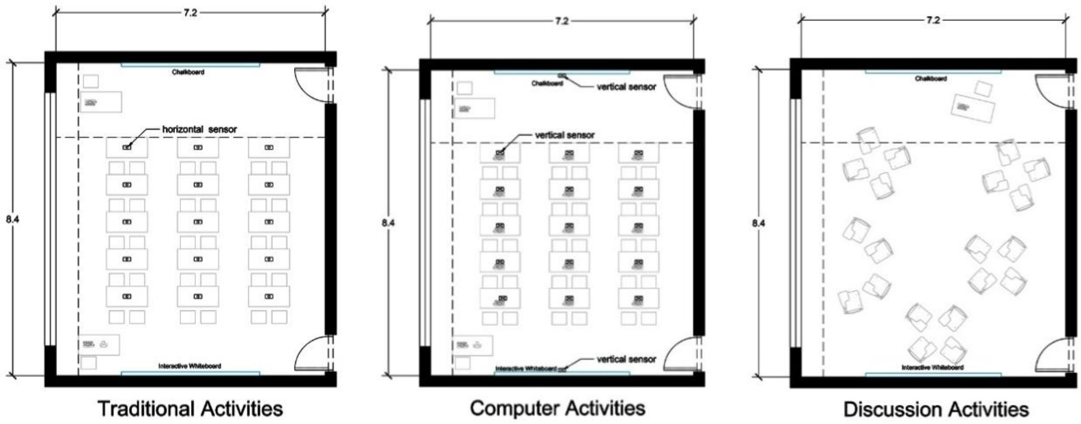

Figure 2. Base case plan show the different activities assigned in the classroom

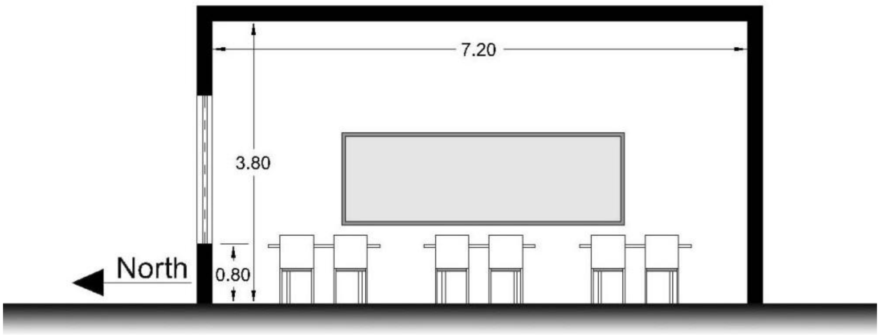

Figure 3. Section of the classroom

2.1. Lighting codes of classrooms' tasks

The tasks performed in classrooms need specific illuminance values depending on the type and nature of the task. According to the European National Standard (EN 12464-1:2002), the writing and reading task needs 300 lux on the horizontal plane (desks plane) and 500 lux on the vertical plane (the board), while the practical-related tasks such as handicraft, arts and experiments need 500 lux[16, 18-20]. Table 1 summarizes the illuminance values required by each task taking place in the classrooms.

Table 1. Illuminance level thresholds (Lux)

Criteria	threshold
Reading on blackboard	500 lux (vertical)
Writing, reading desk	300 lux
Practical activities (Handcrafts, Art and Labs)	500 lux
Coaching computer activities	500 lux (above the computer)

2.2. Daily sunshine at the study area

The virtual model is simulated using the weather data of Amman/Jordan. Amman geographical coordinates are 32 North and 36 East. Figure 4 shows the average monthly hours of sunshine in Amman. The maximum hours of sunshine occur in July with about 390 hours, while December has the lowest amount of sunshine with about 180 hours. The average monthly amount of sunshine in Amman is 274 hours.

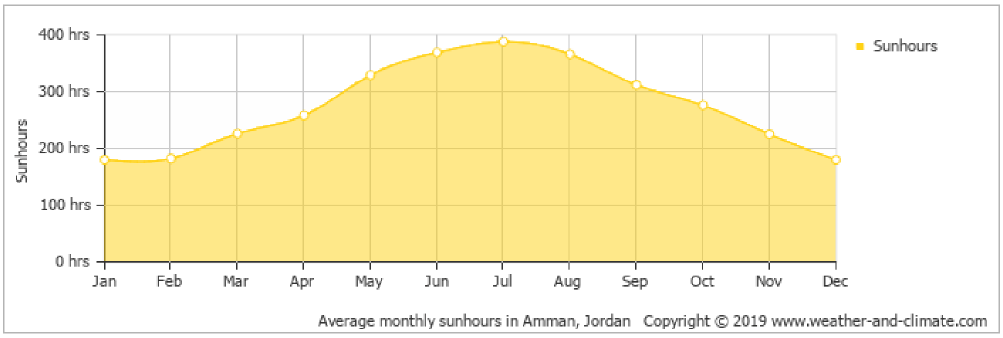

Figure 4. The average monthly hours of sunshine in Amman

3. Methodology

The study focuses on daylighting design in the early stages of building design; hence, it is based completely on the simulation of a virtual model. The case study is a typical elementary school classroom facing north, and it is assumed to be constructed in Amman, Jordan. Different glazing ratios and window configurations impact on visual comfort and lighting requirements was evaluated, using three scenarios for glazing ratio and three sets of window-sill height. The scenarios were selected from [21-26]and it is consistent with the window properties of conventional Jordanian schools. The operational period of schools in Jordan extends from the 1st of September to the 30th of June, from 8:00 am to 3:00 pm and through Sunday to Thursday. The daylight evaluation is conducted at 12:00pm on 21st of June with clear sky condition as the best-case scenario, and at 3:00pm on 21st of December under overcast sky condition as the worst-case scenario. The sun in the sky at Jordan in these specific times is in its highest and lowest positions. All the daylight simulations are performed assuming the use of a typical table, with a height of 0.75m. Illuminance analyses are also conducted for the two critical days using the threshold method, which is the minimum illuminance levels required to achieve occupants' indoor visual comfort[27].Nine classroom prototypes are suggested in this study, as illustrated in Figure 4. Various window-sill heights (S.H) and aperture heights (A.H) besides three scenarios of WWR are evaluated. Model A has WWR set to 20%, and three suggested window-sill heights; 0.8m, 1.2m, and 1.6m. Model B has WWR set to 30%, and it has three alternatives of window-sill height; 0.8m, 1.2m and 1.6m. WWR in model C is 40%, with three suggested window-sill heights; 0.8m, 1.2m, and 1.6m.

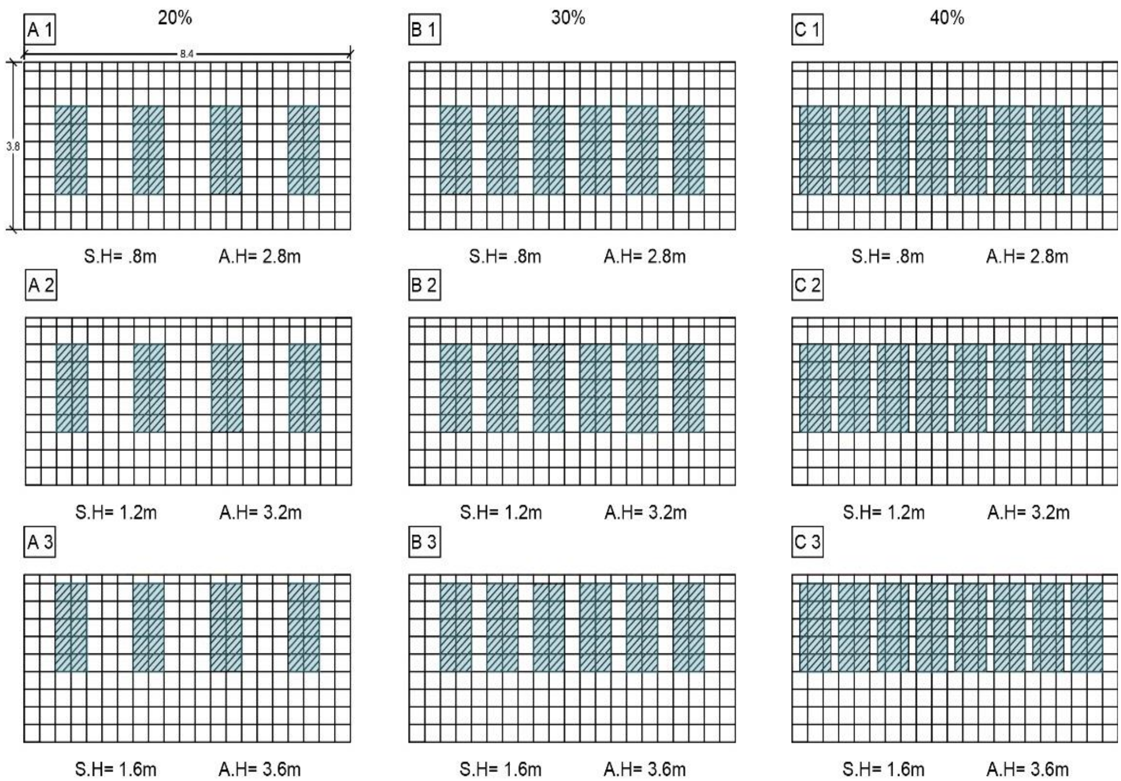

Figure 5. Glazing system combinations scenarios

3.1. Simulation tools

Daylight simulation is carried out using Radiance and Daysim version 3.1b (DDS format). Radiance is used to simulate the illuminance level and distribution, for both horizontal and vertical plane, at a single moment in time and in response to the climate of the area of study.
Radiance simulation results are presented on a grid that shows the daylighting distribution patterns with contour lines. In addition, Radiance results are shown as a rendered scene of the interior that shows the illuminance amount and distribution on the vertical surfaces. The values of Radiance parameters are shown in Table 2.

Table 2. Radiance parameters used in research

Parameter	Description	Value
(-ab)	Ambient bounces	5
(-ad)	Ambient divisions	1000
(-as)	Ambient super-samples	20
(-ar)	Ambient resolution	300
(-aa)	Ambient accuracy	0.1
(-lr)	Limit reflection	6
(-st)	Specular threshold	0.15
(-sj)	Specular jitter	1
(-lw)	Limit weight	0
(-dj)	Direct jitter	0
(-ds)	Direct sampling	0.2
(-dr)	Direct relays	2
(-dp)	Direct pretest density	512
(-ab)	Ambient bounces	5

Annual interior illuminance is measured founded on the weather data of the education area using Daysim. Useful Daylight Illuminance (UDI) is a metric produced by Daysim and it provides the overall availability of useful daylight in the whole year. UDI is divided into three ranges that are determined by upper and lower thresholds; the lower range determines the times when there is no adequate daylight, the upper range determines the times when there is an oversupply of daylight that causes discomfort, and the intermediate range of useful daylight. Table 3 presents the ranges and thresholds of UDI.

Table 3. Overview of tasks in a classroom together with the requirements thresholds.

Metric	Other criteria	Target (thresholds)	
		Minimum	Maximum
Annual illuminance (lux)	UDI 100-2000lux	60%	-
	UDI $_{min}$ <100 lux	-	20%
	UDI $_{max}$ >2000 lux	-	20%

Evalglare is an engine that uses DOS commands. It is used to evaluate glare sources within a 180° fish-eye-image, given in the image format of .pic and. hdr. Radiance images are rendered as fish eye camera using 180° for the horizontal and vertical view angle (-vv =180, -vh=180). The rendered images produced by Radiance are used to evaluate the glare formation and its sources using Evalglare.

4. Results & discussion

4.1. Daylight availability (DA)

The first criterion was the climate-based simulation; it included two targets. The first one being the UDI, or Useful Daylight Illuminance target, this provided the overall availability of useful daylight in a year. The second target is the Electric Light Use, to estimate the electric lighting needed to be used to balance the shortcomings of the daylight[24, 28, 29]. These two targets together indicated the effectiveness of each of the prototypes in terms of the overall availability of useful daylight and the amount of the electric energy needed to cover the times which lack daylight. These criteria satisfy for all sky conditions around the year. The threshold for Useful Daylight Illuminance (UDI) was 100-2000 lux. For this study, the situations were initial assessed for 100-2,000 lux, and subsequently, other thresholds were considered. A target UDI of greater than 60% was considered passing the criteria, while the UDI min & UDI max should not exceed 20% [30]. The results show that (A2, A3, B2, B3) layouts have the optimum annual performance as they attain the target as considered previously (higher than 60% for UDI, while the UDI min and UDI max should not exceed 20%).

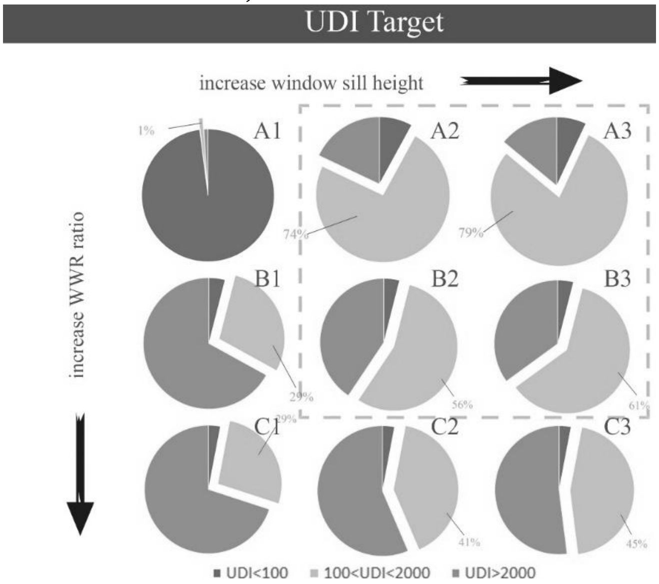

Figure 6. Useful Daylight Illuminance Target (Researcher, 2018)

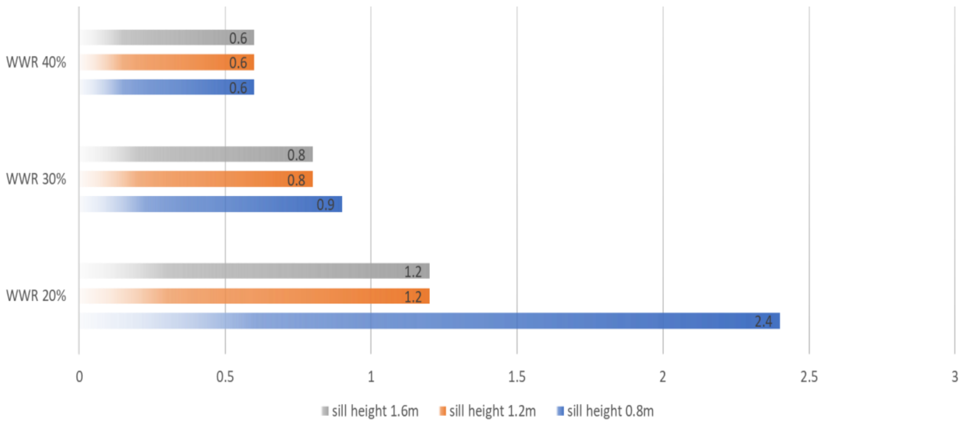

Figure 7. Electric energy demand (kWh/m2yr) for light in the classroom facing North with different WWR ratio and S.H Layouts

4.2. Illuminance distribution

The second criterion was the Single-Time Illuminance Simulation for traditional, discussion and computer tasks performed in the classroom as well as the blackboard. In these criteria, the horizontal and vertical illuminances, as well as the illuminance uniformity, were examined in two points in time, a clear, sunny sky on the 21st of June and an overcast sky on the 21st of December. This part isolated the prototypes that provide best visual performance for the given tasks. Additionally, Illuminance penetration was tested to indicate the places in the classroom that are likely to present glare and visual discomfort. This part provides guidelines for the best locations for placement of desks and chairs in the classroom, and the locations to be avoided. (B1, B2, B3, C1, C2, C3) layouts have the optimum performance that they attain the target of traditional activities while (C1, C2, C3) layouts have the optimum discussion performance. (B1, B2, B3, C1, C2, C3) reach the required target for illuminating the blackboard. On the other hand, a diversity of vertical illuminance distribution is found over blackboard in terms of illuminance ratio, which is recommended to be 0.7 or more, only (B2, B3, C2, C3) layouts approached the target.the target range for computer activities supposed to be (300 lux ≤ X ≤500 lux). Figure 11 illustrates the percentage of area that the classroom could accommodate computer activities and identifies (B1, B2, B3) as the optimum cases.

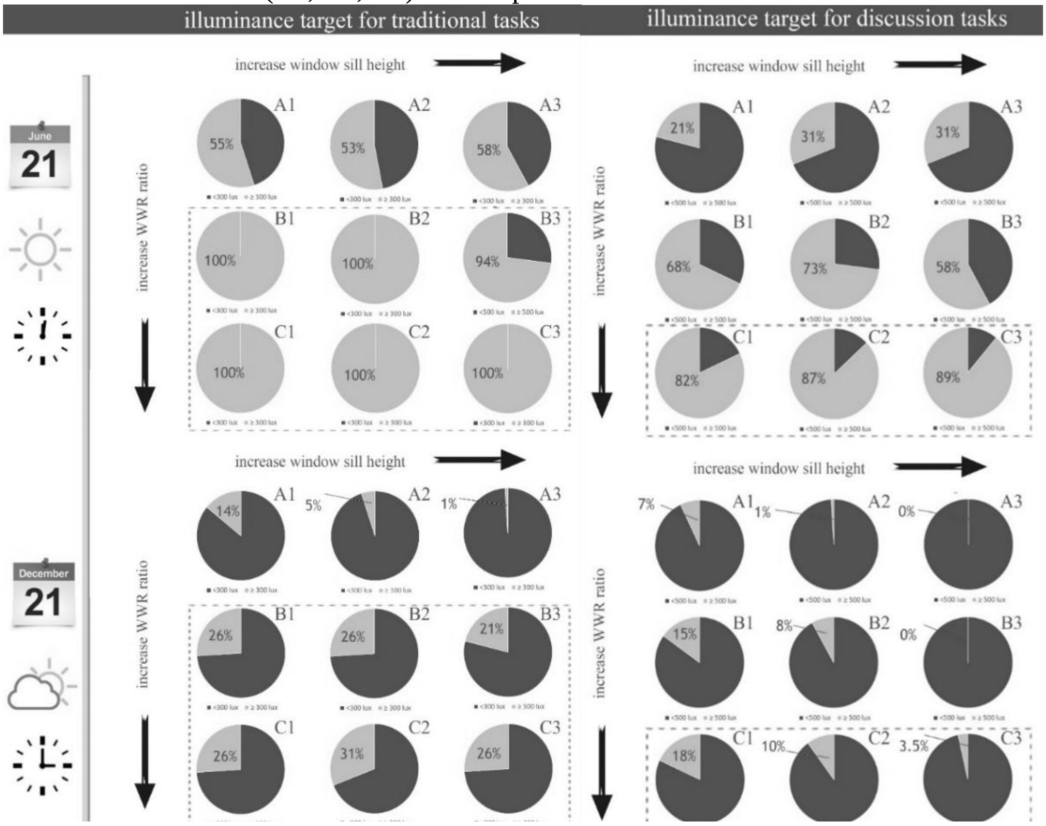

Figure 8. Point-in-time Illuminance results over desk task for traditional and discussion activities

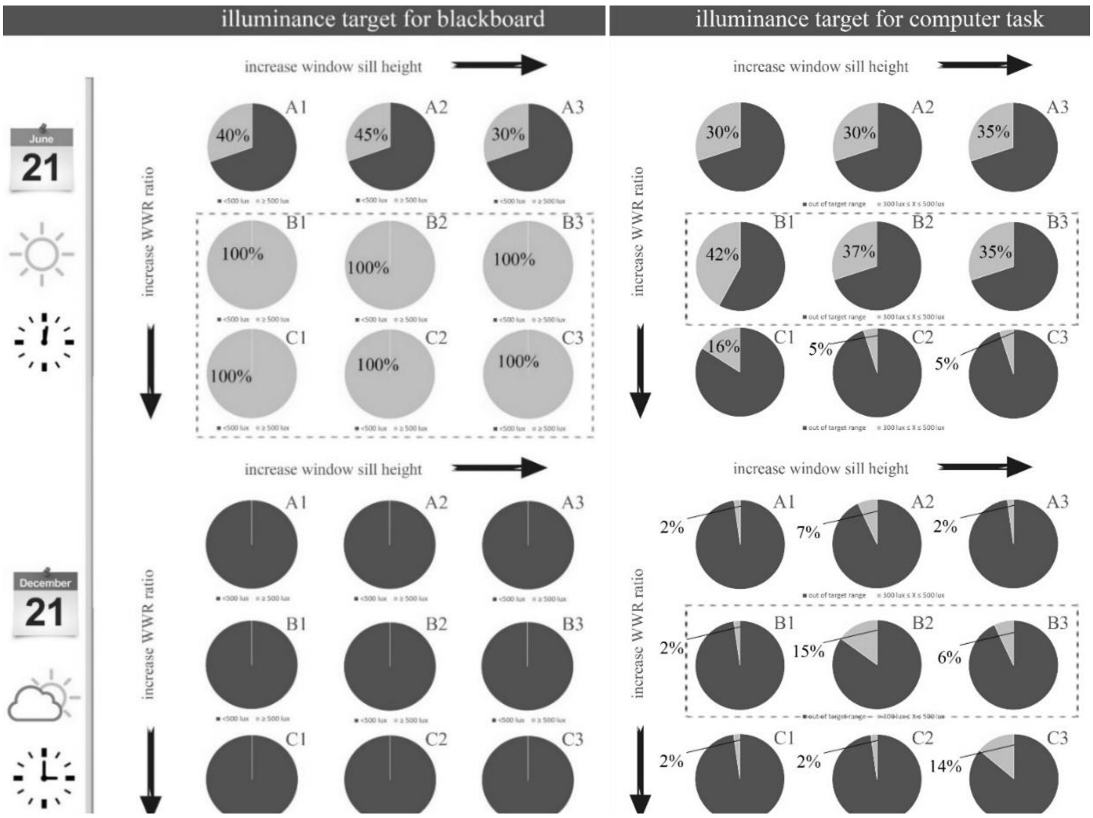

Figure 9. Point-in-time Illuminance results on blackboard and computer screens

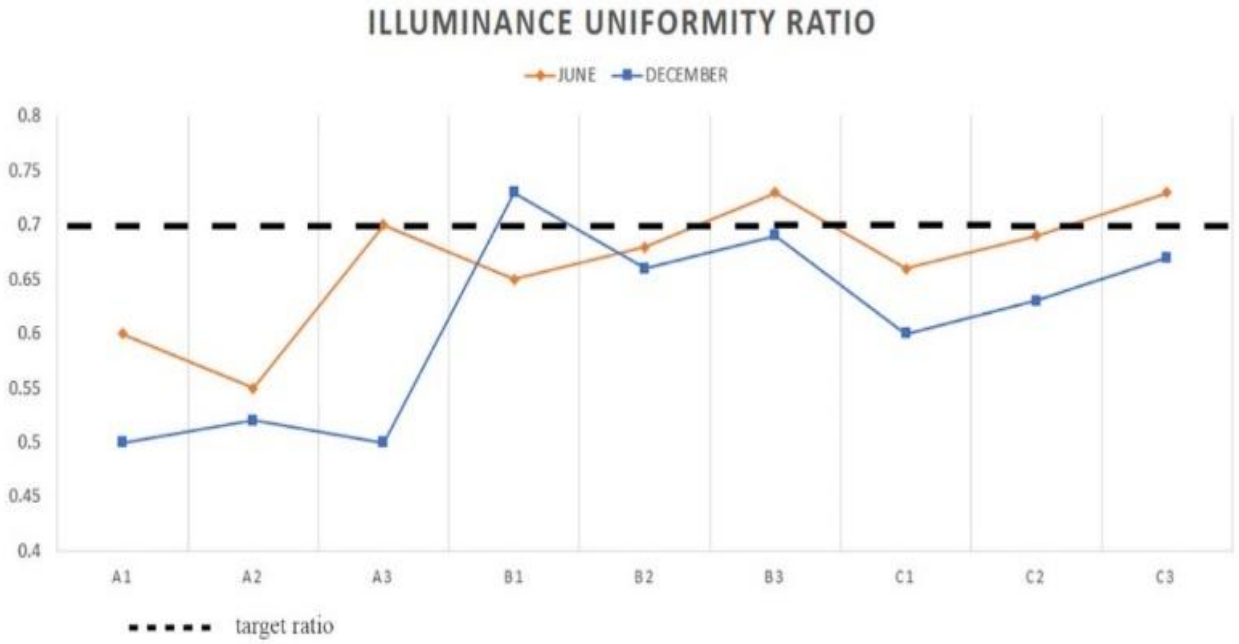

Figure 10. Blackboard illuminance uniformity ratio

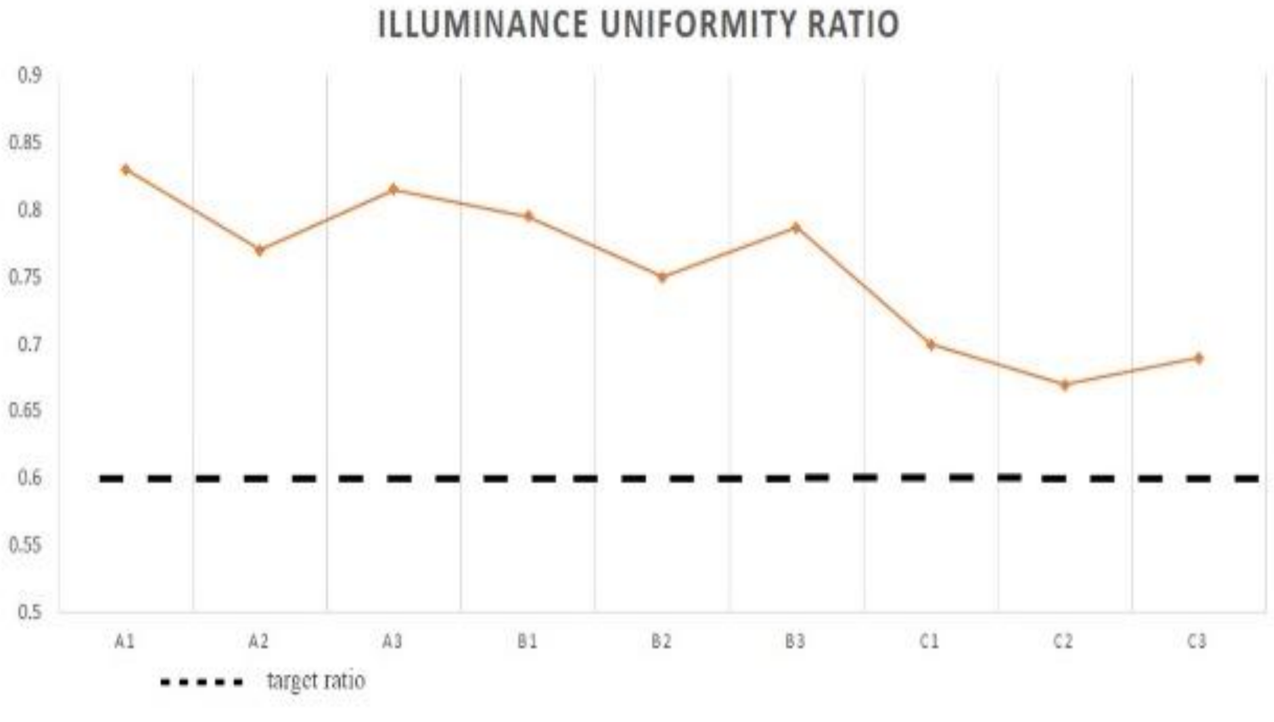

Figure 11. Classroom illuminance uniformity ratio

4.3. Daylighting spread and illuminance uniformity

The uniformity of light describes how evenly light spreads over a task area. Good uniformity of light contributes to avoiding visual discomfort. The recommended ratio of uniformity between the minimum value of the illuminance on the task plane and the average is 0.6 for the classroom and 0.7 for the blackboard (ratio between minimum and average value of the vertical illuminance over blackboard) as discussed for EN 12464-1, and a more uniform distribution is preferred[31].

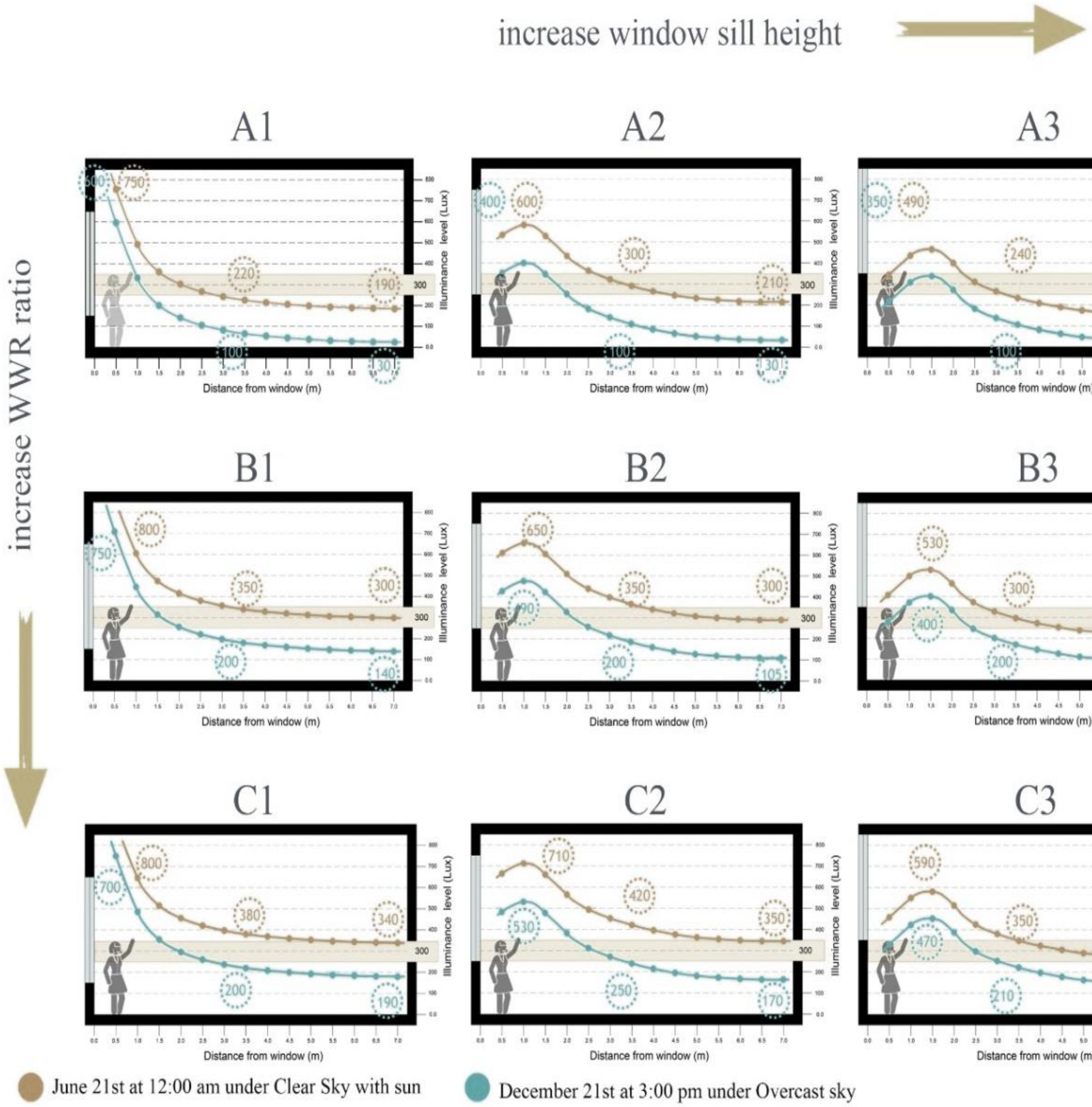

Figure 12. Illuminance penetration-section view

4.4. Visual discomfort and glare analysis

The third criterion was the Point in Time Luminance, which provided analysis of the visual experience and the quality of the light in the classroom based on the acceptable levels of luminance ratios. The fourth criterion was the Point in Time Glare, in which the prototypes were examined in two points in time, a clear, sunny sky on the 21st of June and an overcast sky on the 21st of December. This simulation was performed taking into consideration the position of a student sitting in the back of the class and looking at the centre of the blackboard. The results identify the prototypes that provide the best possible visual comfort[9, 27, 32].

4.5. Point-in-time luminance

However, a point-in-time luminance rendering is important to understand the visual perception and experience of the daylighting environment. Point-in-time luminance generates visualisations via false colour rendering images showing the distribution of light through the space and also numeric amounts and luminance ratios. The criteria used in this thesis for the point-in-time luminance involved the contrast ratios between paper and VDU screen to prevent potential glare risk. The European norm EN 12464-1 recommends that luminance ratios do not exceed the value of (1:3) task desk: VDU screen [29, 33-35].

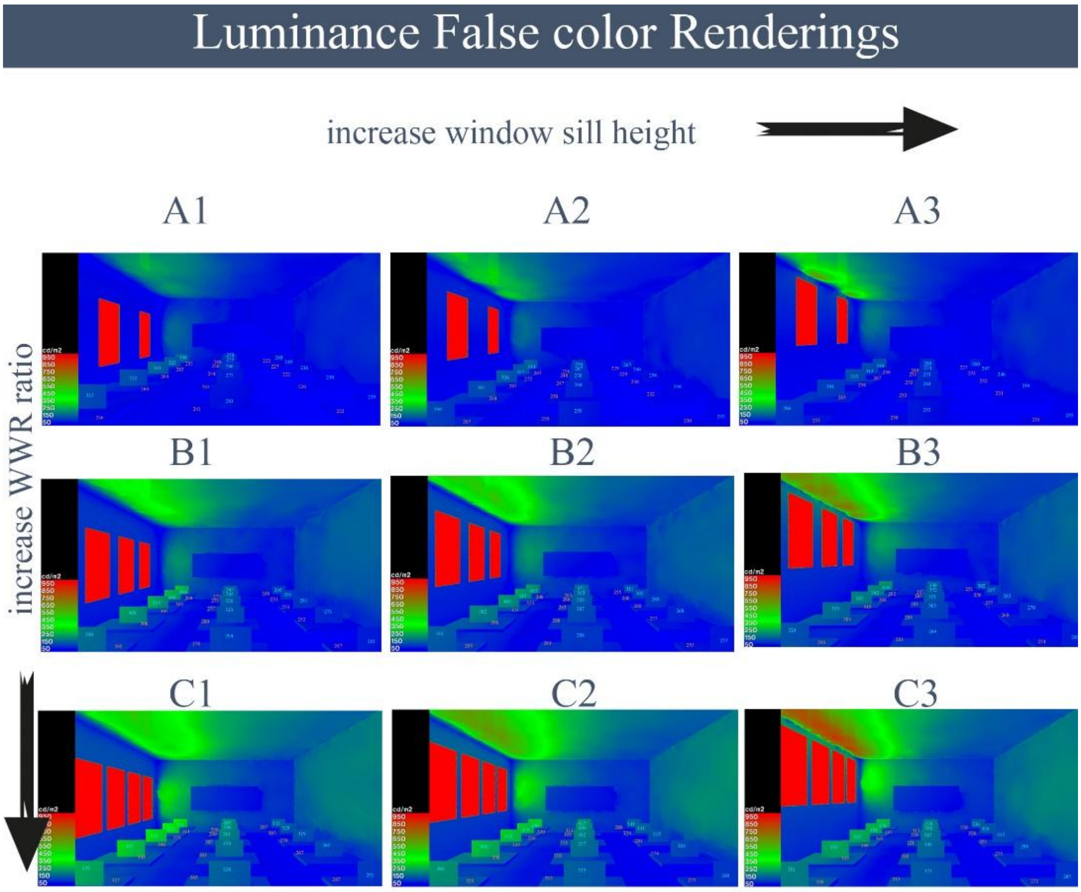

Figure 13. Luminance false colour renderings

4.6. Point-in-time glare

The simulation will produce a fisheye luminance rendering as shown in the analyzed data presented, with coloured areas indicating potential glare sources and a calculated value for DGP, glare thresholds discussed in the literature review chapter (see table below), it was determined that a DGP of 40% or above would be considered an uncomfortable environment. The results show that the influence of the sill height on the visual comfort, performance and glare probability is slightly defined while the effect of WWR ratio has radically changes. The layouts (C1, C2, C3) exceed the limit of comfort zone which means a high chance of glare discomfort.

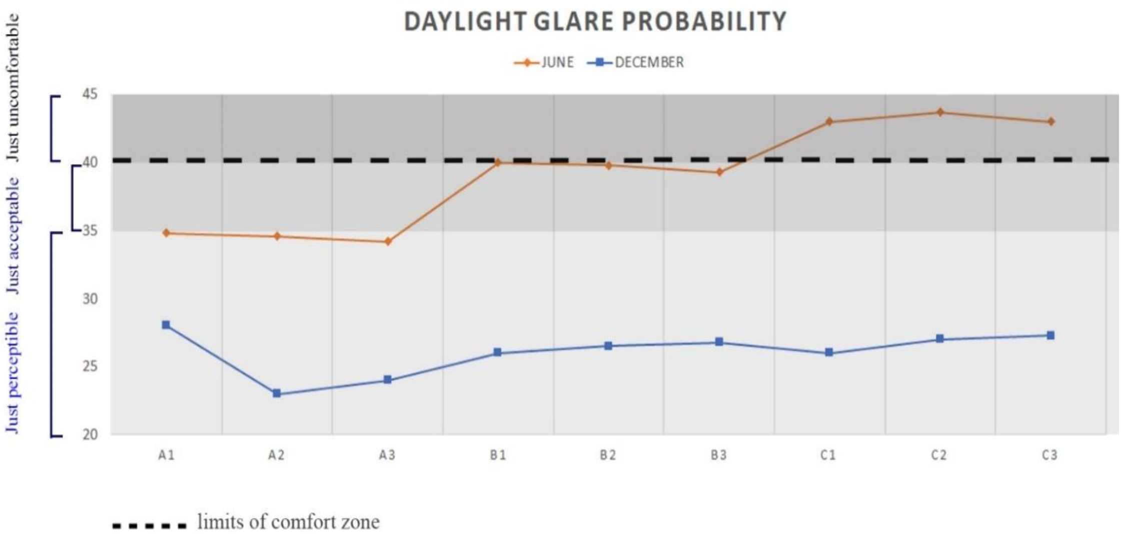

Figure 14. Daylight glare probability

As a conclusion and after simulations were carried out, also if certain metrics are more useful than others, none of them are an obvious determinant of the efficiency of the space; none of the scenarios comply with 100 per cent. That is, if a single metric were to be used, different design decisions might be taken than if multiple analyzes were carried out to consider various aspects of the luminous environment: light levels, visual perception, visual output, visual comfort, and variability.
summarized table of the nine typologies results followed by a short description of the findings will be discussed below. the table below weighs all metrics with equal status, as the goal is determined the fitness with the criteria for each singular metric. The usability of the metrics is variable.

	Metric name		Alternate A1		Alternate A2		Alternate A3		Alternate B1		Alternate B2		Alternate B3		Alternate C1		Alternate C2		Alternate C3	
			June	Dec	June	Dec	June	Dec	June	Dec	June	Dec	June	Dec	June	Dec	June	Dec	June	Dec
daylight availability	Point-in-time illuminance	Reading on blackboard	40%	0%	45%	0%	30%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%
		Writing, reading desk	55%	14%	53%	5%	58%	1%	100%	26%	100%	26%	99%	21%	100%	26%	100%	31%	100%	26%
		Practical activities (Handicraft, Art and laboratories)	21%	7%	31%	1%	31%	0%	68%	15%	73%	8%	58%	0%	82%	18%	87%	10%	89%	3.5%
		Coaching computer activities	30%	2%	30%	7%	35%	2%	42%	2%	37%	15%	35%	16%	16%	2%	5%	2%	5%	14%
	Annual illuminance	UDI 100-2000lux	1% ○		74% ●		79% ●		29% ○		56% ○		61% ●		27% ○		41% ○		45% ○	
		UDI $_{min}$ <100 lux	98% ○		8% ●		7% ●		4% ●		4% ●		4% ●		3% ●		3% ●		3% ●	
		UDI $_{max}$ >2000 lux	1% ●		18% ●		14% ●		67% ○		41% ○		35% ○		70% ○		57% ○		52% ○	
	Illuminance Uniformity	Of classroom	0.83 ●		0.77 ●		0.82 ●		.79 ●		.75 ●		0.78 ●		0.7 ●		0.67 ●		0.69 ●	
		Of blackboard	0.6 ○	0.5 ○	0.55 ○	0.52 ○	0.7 ●	0.5 ○	0.65 ○	0.73 ●	0.68 ○	0.66 ○	0.73 ●	0.69 ○	0.66 ○	0.6 ○	0.69 ○	0.63 ○	0.73 ●	0.67 ○
	Electrical light use	(Kwh/unit area)	2.4		1.2		1.2		0.9		0.8		0.8		0.6		0.6		0.6	
visual discomfort and glare	Point-in-time luminance		contrast ratios between paper and VDU screen for all the cases are also equal to or below the target 1:3																	
	Daylight glare Probability		34.8% ●	28% ●	34.6% ●	23% ●	34.2% ●	24% ●	40% ●	26% ●	39.8% ●	26.5% ●	39.3% ●	26.8% ●	43% ○	26% ●	43.7% ○	27% ●	43% ○	27.3% ●

% fitness

● meets criteria
○ does not meet criteria

Figure 15. Compliance for all cases

5. Conclusions

This research aimed to improve the daylighting performance of a virtual classroom model that is assumed to be built in Amman, Jordan. The model is a representation of the typical elementary classrooms of Jordan. The research intended to achieve a flexible design, where daylight can be used for all the operational time of the classroom, and taking into consideration the various learning activities taking place in the classroom and their illumination requirements, such as discussions, traditional learning and using computers. Nine classroom prototypes, with different WWRs and window-sill heights, were suggested and evaluated using computer simulation.

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