USING SOLAR SCREENS IN SCHOOL CLASSROOMS IN HOT ARID AREAS:
THE EFFECT OF DIFFERENT PERFORATION RATES ON DAYLIGHTING LEVELS

AHMAD KOTBI[1,2], ELENI AMPATZI[1]

[1]Welsh School of Architecture, Cardiff University, Cardiff, UK
[2]College of Architecture & Planning, King Saud University, Riyadh, Saudi Arabia

ABSTRACT: Hot arid areas are endowed with an abundance of clear skies. Thus, the solar energy available can significantly raise the temperature of interior spaces and also result in an uncomfortable visual environment due to glare and poor uniformity ratios. This paper focuses on a special case of girls' schools in Saudi Arabia, where the privacy issue is critical due to socio-cultural and religious beliefs. Most windows in girls' schools are covered by dark opaque film to maintain privacy. This window treatment brings the need for electric lights, which makes schools huge consumers of energy considering the peak time operational hours and the large number of schools. This paper looks at how different perforation rates affect the performance of screens by simulating 10 different ratios from 10% to 90% and a base case without a screen. First, the effect was tested on average illuminance levels, and then on Daylight Availability by using the Daylight Dynamic Performance Metrics approach (DDPM). The results specify the minimum perforation rate to provide the required average illuminance in each orientation and give a tool to decide perforation rates according to the required percentage of daylit area in contexts similar to the studied space.
Keywords: Daylight, Solar Screens, Schools, Privacy, Daylight Availability, Daylight Dynamic Performance Metrics.

INTRODUCTION

Hot arid areas are endowed with an abundance of clear skies. Thus, the solar energy available can significantly raise the temperature of interior spaces and also result in an uncomfortable visual environment due to glare and poor uniformity ratios [1]. A shading device called a "Mashrabiya" has been traditionally used in some of these areas. Mashrabiyas are fixed in front of windows to control solar penetration, a concept that is now being broadly adopted in solar screens [2], but have also a social function of maintaining privacy which is an important issue in Islamic cultures [3]. The dual purpose of this device explains the spread of its use around the world wherever Muslims exist, from Moorish Spain in the West through North Africa and the Middle East to India in the East [4].

The privacy issue for women is important in Saudi Arabia as the country follows an Islamic law, which means women should be covered in the presence of unrelated men. Following the same law, women wear a black robe called an "Abaya", which they can only remove at women-only events, their houses or in buildings occupied by women only, such as girls' schools. In the latter environments, it is common practice for the windows to be completely covered by black opaque coatings or non-transparent curtains to maintain privacy.

These treatments are known to have an effect on the occupants' health, wellbeing and efficiency due to lack of adequate daylight and access to external views [5, 6]. Using perforated screens could be a solution for this situation to maintain privacy and at the same time improve interior daylight conditions. Although there are many solutions during the design process such as using courtyards, this research focuses on retrofitting existing buildings.

The performance of perforated screens is affected by many parameters and previous studies have summarised these to be: perforation rate, depth ratio, shape, reflectivity of colour, aspect ratio of openings, tilt and rotation angles [7]. This paper is a part of an ongoing research that examines the parametric design of perforated screens for both enhancing interior daylight levels and maintaining privacy in typical girls' classrooms in a hot arid area.

OBJECTIVE

The objective of this paper is to define optimum perforation rates for solar screens in order to optimise interior daylighting for each main orientation in the context of schools in hot arid areas. Different perforation rates are later going to be studied in relation to privacy as the next step to this research.

Previous studies have already investigated the effect of different parameters of perforated screens on daylight in living rooms in residential spaces, namely, perforation rate, depth ratio, axial rotation [2, 7, 8]. However, results would be different for educational spaces, due to different illuminance requirements, different window to wall ratio, space size, dimensions and hours of occupancy when compared with residential spaces.

SIMULATION

The experiment is conducted using virtual simulation using the following software: "Rhinoceros" often abbreviated as 'Rhino' which is used to build the 3D model, it is a 3D modelling tool with the capability to create and analyse complex geometry. "DIVA-for-Rhino" often abbreviated as 'DIVA' stands for "Design Iterate Validate Adapt" [9], is an environmental analysis plug-in for Rhinoceros-3D and is used as an interface for the simulation engines: Radiance and Daysim [10], and it performs a daylight analysis on an existing architectural model [11]. "Radiance", developed by GregWard at Lawrence Berkely National Laboratory, works with the ray trace backward technique for the precise daylight calculations on which most of the daylighting software tools are based [12], and It has previously been validated [13, 14]. Daysim calculates the annual performance in the form of Daylight Autonomy that represents the percentage of occupancy hours where daylight achieved the target illuminance [15] it also has been validated based on physical measurments [10, 16]. "Grasshopper-3D" developed by David Rutten at Mcneel & Associates [17], is used in this study with Rhino to produce 3D models of solar screens with different perforation rates, Grasshopper is a generic algorithm editor allowing the user to perform parametric modelling extension for Rhino. Parametric modelling refers to the automated parameter based generation of 3D elements [18]. In this study, screens are automatically drawn based on author's defined algorithms and can be altered by changing parameters within the algorithm according to the required result. Grasshopper can also be used with DIVA to control and increase the workflow of simulation runs and export results [19]. The DIVA component in Grasshopper is used in this study to control DIVA-for-Rhino and export results to "Ms-EXCEL".

The location of analysis is Riyadh, which lies on Latitude 24.7, Longitude 46.80 and elevated 612 m above sea level. The weather data file for Riyadh is used for simulation, obtained from the U.S Department of Energy [20]. The weather data contains a generated Typical Meteorological Year "TMY"; it contains 12 Typical Meteorological Months "TMM" selected from recorded data for about 23 years [21]. The data to produce this file was recorded in King Khaled Airport in Riyadh.

The simulated sky condition was set as 'clear sky with sun' as this is the typical sky in such climate. The weather in Riyadh is very hot as it is surrounded by deserts; the average daily maximum temperature is 41°C in summer and can reach 50°C in extreme cases. In winter, the average daily temperature is 14°C, and the minimum temperature can reach -2°C in extreme cases. The external illuminance in such climate can reach up to 100,000 lx in Summer [22].

Simulation parameters are presented in (Table 1), an ambient division of 1000 was recommended to avoid resulting in high brightness variation [23-25]. Ambient accuracy is chosen to be 0.1, being adequate since the smallest opening was not less than 0.005m [7]. The ambient bounces are the number of times the light hits any plane and it is recommended to be 6 [23, 24]. However, only for the first stage of the analysis presented here, the ambient bounces is chosen to be 3 instead of 6 to reduce the extremely long processing time resulted by the complexity of screen geometry. This has been justified previously by comparing results of identical simulation models using different ambient bounces [25]. The experiment is repeated for the four main orientations.

Table 1: Utilized Radiance Simulation Parameters.

Ambient bounces	Ambient divisions	Ambient sampling	Ambient resolution	Ambient accuracy
6	1000	20	300	0.1

ARCHITECTURAL PARAMETERS

The simulated space (Fig. 2&3) and the indoor parameters represent an average classroom in Riyadh [N24.63°, E46.72°] the capital of Saudi Arabia. The typology used is based on 11 classrooms that the researcher visited and monitored in summer 2015 [26], with the dimensions slightly adjusted to allow the space to be divided into three zones with the same number of measuring points 'zones distinction explained below'. A typical classroom has five windows, the dimensions of windows are also adjusted from 1.25×0.75m to 1.2×0.72m in order to have the ability to be divided equally for further investigation (cell size, aspect ratio and depth ratio). (Table 2) presents the assumed parameters for the modelled classroom and the reflectance values of indoor surfaces as recommended by Illuminating Engineering society [23]. Four streets surround most schools in Riyadh, and there is a scarcity of trees since it is a desert environment. Therefore, external obstructions are ignored in simulation, the external walls were assumed to have beige colour with a reflectance of 35%.

Table 2: parameters of the simulated classroom and screen

Space parameters	
Dimensions	4.50m × 6.90m × 3.00m
Working Level	+0.75m
Surfaces reflectance	
Interior walls	50%
Exterior walls	35%
Ceiling	80%
floor	20%
furniture	50%
White Board	90%
Solar screen	70%
Windows parameters	
Window to wall ratio “WWR”	21%
Number of windows	5
Dimensions	0.72m × 1.20m
Sill height	1.15m
Transmission	88%
Solar screen parameters	
Cell size	0.06m × 0.06m
Depth	0.045m
Depth ratio	0.75
Reflectance	70%

SCREEN PERFORATION

Since the focus of this paper is on perforation rates, other screen parameters remain fixed and assumed as follows:

- Horizontal to Vertical aspect ratio of 1:1
- Module size was 6×6 cm. (Fig. 1)
- Depth ratio of 75% ‘module size / depth’
- Colour reflectance: 70%.

Each window is divided into a 6×6cm module, which gives 240 perforation. The perforation rate is calculated considering the module grid and each hole were concentric with it. (Fig. 3) represents examples of two screens, with 50% and 90% perforation rates.

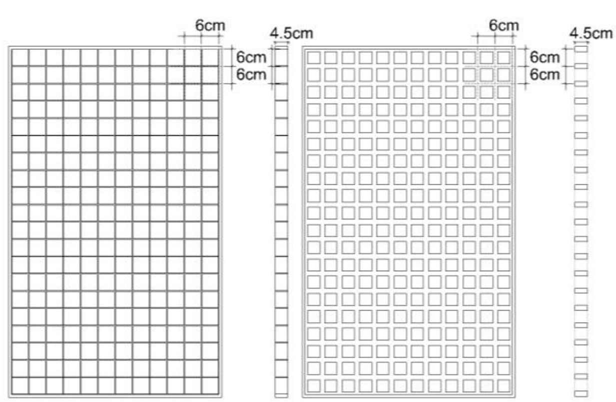


Figure 1: screen module, an elevation and a section of an example of 50% perforation rate on the right and 90% perforation rate on the left.

METHODOLOGY

Experiments are conducted in two stages. First, daylight illuminance levels at specific times and days are analysed using measuring points spread on a reference plane to calculate interior illuminance at each point.

The Illumination Engineering Society recommends the height of the working plane to be just above the highest regular task in the space, which is for classrooms, reading and writing on desks [23]. Therefore, the working plane is set at 0.75m height (Fig. 2), just above the top of pupils’ desks as measured in an actual classroom in Riyadh [26]. The reference plane has 345 measuring points evenly distributed in a 0.3×0.3m grid, and divided equally into three zones, each zone having 115 measuring points, zones are named according to the distance from the window (Near zone, Mid zone, Far zone) as explained in (Fig. 3). The 0.3×0.3 grid is chosen as the minimum recommended distance to improve accuracy [23]. This method was used before in similar related studies [2, 25].

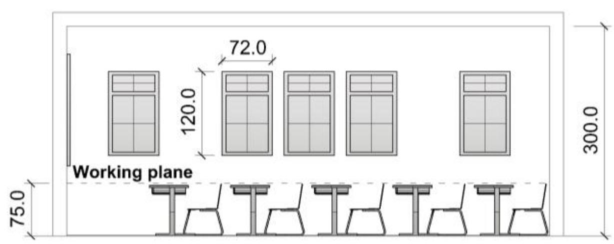


Figure 2: Base case classroom section showing windows and height of working plane.

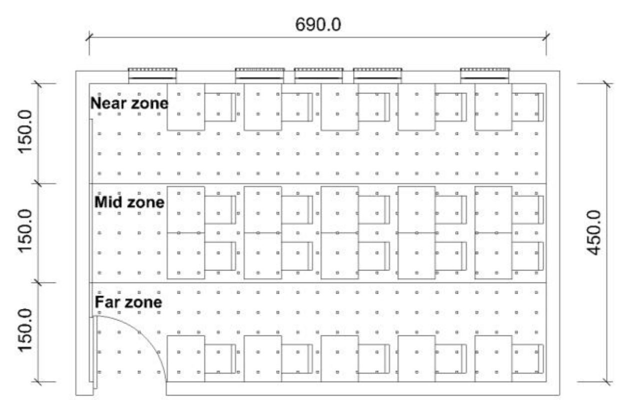


Figure 3: Base case classroom plan and zones.

In the second phase, the effect of different perforation rates on the annual performance is tested by using Dynamic Daylight Performance Metrics “DDPM”. These metrics evaluate daylighting performance based on time series of illuminance or luminance levels within a space. These time series cover the occupancy hours in a calendar year and are based on external, annual solar radiation data for the building site [15]. These metrics include Daylight Autonomy “DA”, Useful Daylight Illuminance “UDI” and “Daylight Availability”. “DA” which is defined as the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone, and then categorize the space according to that into two criteria: ‘Daylit area’ and ‘Partly Daylit area’. Daylit area is the area achieving the required threshold for at least half of the occupied time, whereas, areas that fail to achieve the required threshold are considered Partly lit area [10]. “UDI” uses upper and lower threshold of 100lx and 2000lx to determine illuminance within a useful range [27]. “Daylight Availability” however, was developed to combine both “DA” and “UDI”. When using this metric, the space is categorized into three classifications, according to the daylight availability criterion. “Daylit” areas are the areas receiving adequate daylight for at least half of the occupancy time, “Partlylit” areas are the areas receiving adequate daylight for less than half of the occupancy time, “Overlit” areas are the areas receiving ten times or more of the adequate daylight for at least 5% of the occupancy time [24]. The 5% criterion was selected according to British Standards [28].

The standard adequate illuminance for a reading and/or writing task is 500lx [29], however, it is very difficult to depend on daylight solely to achieve this level without causing glare. Therefore, the adequate illuminance level was set to 300lx since the aim was to reduce the use of artificial light as possible [23, 30].

The occupancy times are chosen from a typical school year in Saudi Arabia, which has 36 weeks a year i.e. 180 days with a total of 1080 hours, school year often starts in mid-September until mid-June in two semesters, each one has one half-term break

PHASE I: AVERAGE ILLUMINANCE

In this phase, average interior illuminance of the 115 measuring points for each zone is calculated for the “no screen” case and nine other cases from 90% to 10% perforation rate, by simulating 3 specific times in four specific days under a clear sky condition. These days are chosen to be spread between each season (summer, autumn, winter, spring) and being a school day in a typical school year in Saudi Arabia. The simulated times were selected to be (07:00, 09:30, 12:00), considering the fact that school hours in Saudi Arabia start from 6:45 to 12:30 due to the hot ambient temperatures in the afternoon hours. The simulation process is repeated for the four main orientations (East, North, West and South). Most similar experiments have used only three orientations: North, South and either East or West, given that the sun path is symmetrical; therefore, the result of 09:00 and 15:00 in the West would be the same as the result of 15:00 and 09:00 on the East respectively [8]. This was not applicable in this study since the selected hours for the simulation were (07:00, 09:30, 12:00), thus, not symmetrical between East and West.

The average illuminance was calculated for each zone excluding measuring points with more than >5000lx, because including these points would bias the average values although they stand for less than 0.5% of the measuring points [25]. Then, the average illuminance of each case in each zone is displayed in a table for each orientations (Table 3, 4, 5&6). That allows producing a table for the recommended perforation rate for each case (Table 7).

RESULTS OF PHASE I

The results show that using perforating screens in most cases maintains the percentage between readings of average illuminance in Near, Mid and Far zones. Thus, maintain the light distribution and uniformity within the space. The only exception was noon in summer for all orientations (Table 3,4,5&6), and 7:00 in winter and spring for East orientation, (Table 4). In the later cases, percentage of average illuminance in Far and Mid zones are reduced with the use of solar screens, thus less daylight uniformity.

Table 3: Average Illuminance for each case in the three zones of the South orientation, highlighting cells (black) with ≥300lx, (grey) between 200lx and 299lx.

South Orientation													
Seoson		Summer			Autumn			Winter			Spring		
Time		7	09:30	12	7	09:30	12	7	09:30	12	7	09:30	12
Near	no screen	181	240	626	151	301	369	214	512	521	116	365	467
	90%	110	135	368	86	176	208	86	300	345	70	215	265
	80%	102	120	330	77	151	182	74	261	304	63	188	230
	70%	92	108	296	68	133	155	63	217	257	54	157	193
	60%	86	93	261	59	111	130	52	179	215	46	129	156
	50%	84	89	245	57	102	118	48	158	186	44	116	141
	40%	71	75	205	44	77	86	34	105	130	33	81	97
	30%	66	65	185	40	62	69	27	76	90	29	64	72
	20%	61	59	167	35	50	55	22	53	58	25	49	53
	10%	57	55	153	31	43	46	18	37	40	22	39	41
Mid	no screen	211	312	832	356	454	572	429	820	873	172	584	767
	90%	92	128	355	206	224	286	107	465	556	76	298	406
	80%	78	107	291	86	190	241	91	390	478	67	255	344
	70%	65	90	241	74	153	195	73	324	408	54	200	280
	60%	53	73	189	61	119	152	57	256	327	42	161	216
	50%	52	67	179	45	108	139	51	227	282	38	143	197
	40%	37	46	118	30	66	81	31	131	177	24	84	110
	30%	30	33	85	23	46	56	20	76	102	19	53	69
	20%	23	26	61	16	29	33	12	40	51	11	31	38
	10%	20	21	48	12	19	22	7	19	22	8	19	21
Far	no screen	260	424	1327	344	750	927	382	1121	1045	238	963	1098
	90%	75	119	311	278	251	345	118	599	693	72	355	527
	80%	63	100	253	76	208	284	99	503	597	61	301	438
	70%	52	82	202	62	168	226	76	405	503	48	235	350
	60%	40	63	156	52	127	172	59	313	413	36	179	268
	50%	40	61	149	38	119	159	56	281	347	34	168	245
	40%	24	36	83	21	62	82	29	149	218	19	85	124
	30%	18	25	61	16	41	53	17	85	121	12	52	71
	20%	13	17	35	9	21	26	8	37	53	7	25	33
	10%	10	12	26	6	12	14	4	13	16	4	12	14

Table 4: Average Illuminance for each case in the three zones of the East orientation, highlighting cells (black) with ≥300lx, (grey) between 200lx and 299lx.

East Otientation													
Seoson		Summer			Autumn			Winter			Spring		
Time		7	09:30	12	7	09:30	12	7	09:30	12	7	09:30	12
Near	no screen	806	482	619	777	449	255	1133	385	218	2061	458	242
	90%	483	274	372	579	286	144	519	226	121	1247	289	137
	80%	421	237	338	506	244	129	432	192	109	972	244	120
	70%	348	200	297	424	205	115	364	164	98	811	211	107
	60%	282	160	273	349	165	99	305	138	87	531	175	93
	50%	248	142	256	294	149	95	283	121	81	465	157	89
	40%	164	96	217	203	98	78	198	82	66	261	104	71
	30%	111	72	195	135	74	69	98	65	61	277	75	64
	20%	67	53	179	83	54	63	33	47	63	96	53	56
	10%	37	42	167	45	40	58	21	36	50	38	39	51
Mid	no screen	1078	787	790	907	746	331	659	642	286	1220	755	324
	90%	687	424	324	594	446	136	339	326	114	930	443	131
	80%	585	351	275	512	367	115	284	272	96	874	380	112
	70%	488	287	234	436	301	97	229	221	79	713	315	94
	60%	303	222	187	354	232	78	183	175	64	657	245	76
	50%	345	196	168	307	210	71	159	157	58	622	216	68
	40%	216	112	110	204	118	47	93	88	39	286	124	45
	30%	135	70	79	138	71	36	55	59	30	188	77	36
	20%	68	39	63	80	40	27	25	33	27	205	40	25
	10%	23	21	50	30	21	21	10	18	18	18	20	19
Far	no screen	1028	1173	1219	816	1036	457	564	1057	377	535	1004	456
	90%	691	544	283	538	565	129	297	394	104	305	568	131
	80%	592	450	235	476	468	108	255	328	88	261	473	105
	70%	497	359	189	408	375	88	211	258	71	220	392	85
	60%	325	274	143	345	287	69	168	199	55	181	303	67
	50%	353	253	140	297	263	64	147	185	53	158	273	64
	40%	229	127	80	211	134	37	85	94	30	105	142	37
	30%	145	74	55	144	78	26	55	58	22	71	82	28
	20%	74	32	38	82	35	17	26	27	17	40	36	16
	10%	19	14	27	29	14	13	7	11	10	16	14	11

Table 5: Average Illuminance for each case in the three zones of the North orientation, highlighting cells (black) with ≥300lx, (grey) between 200lx and 299lx.

North Orientation													
Seoson		Summer			Autumn			Winter			Spring		
Time		7	09:30	12	7	09:30	12	7	09:30	12	7	09:30	12
Near	no screen	213	247	617	144	240	279	116	282	281	105	256	277
	90%	131	137	369	81	146	171	81	204	191	62	168	179
	80%	114	123	337	71	132	155	78	195	179	57	156	166
	70%	100	108	300	64	120	144	73	183	169	51	146	151
	60%	83	95	271	57	111	131	70	174	155	46	135	141
	50%	78	89	260	54	102	127	65	167	149	42	128	136
	40%	59	72	229	45	93	114	61	159	136	36	115	121
	30%	48	63	197	39	82	102	59	148	127	33	111	112
	20%	39	55	175	36	75	94	57	144	122	30	102	106
	10%	34	50	102	33	72	90	55	142	119	28	99	102
Mid	no screen	330	334	791	190	281	312	111	263	296	135	271	300
	90%	157	142	333	74	119	138	49	132	149	54	119	139
	80%	133	117	279	64	102	119	44	119	134	46	106	122
	70%	109	97	233	52	88	101	37	105	118	38	90	104
	60%	85	79	180	41	72	84	32	90	106	30	74	88
	50%	80	71	166	38	67	80	28	87	99	28	69	82
	40%	47	46	115	24	49	63	22	74	84	20	51	65
	30%	34	36	84	19	37	46	19	62	71	15	42	52
	20%	21	25	64	14	30	37	16	56	64	11	36	45
	10%	14	19	40	12	25	32	14	51	60	9	31	40
Far	no screen	533	473	1223	240	355	388	129	283	309	169	324	349
	90%	165	137	288	64	111	126	36	102	115	43	106	121
	80%	137	112	237	51	92	106	30	89	100	37	89	102
	70%	111	92	185	43	76	86	24	77	85	28	73	85
	60%	86	70	148	32	61	71	20	64	73	23	60	70
	50%	82	67	141	31	56	67	20	63	69	21	57	67
	40%	43	37	101	18	43	50	13	45	51	14	38	50
	30%	30	29	56	13	25	32	11	38	41	9	29	34
	20%	15	17	38	8	19	23	8	32	35	6	22	26
	10%	8	12	22	6	15	18	7	30	31	5	19	22

Table 6: Average Illuminance for each case in the three zones of the West orientation, highlighting cells (black) with ≥300lx, (grey) between 200lx and 299lx.

West orientation													
Seoson		Summer			Autumn			Winter			Spring		
Time		7	09:30	12	7	09:30	12	7	09:30	12	7	09:30	12
Near	no screen	215	268	619	195	274	263	149	240	231	211	277	240
	90%	143	171	367	136	183	148	115	161	131	170	188	134
	80%	135	158	334	127	169	134	110	150	119	162	178	120
	70%	125	145	302	120	159	117	105	141	102	156	166	108
	60%	115	133	265	112	145	101	100	130	90	150	156	96
	50%	110	128	249	107	140	96	98	128	83	147	152	88
	40%	100	113	205	97	127	78	92	115	68	140	136	74
	30%	92	105	185	92	116	68	88	108	61	136	128	65
	20%	87	97	167	89	112	60	87	103	51	133	123	58
	10%	83	94	156	84	107	55	85	99	47	130	120	53
Mid	no screen	252	299	842	219	304	358	216	255	317	289	293	315
	90%	135	141	351	117	147	150	155	124	135	215	147	129
	80%	119	122	300	107	133	128	147	109	115	208	135	111
	70%	109	106	239	94	115	106	141	96	95	199	117	92
	60%	97	90	198	85	101	84	134	85	75	191	105	76
	50%	93	85	181	84	94	78	133	81	70	190	100	68
	40%	78	64	115	67	75	51	124	64	45	180	82	45
	30%	69	55	85	61	68	39	120	55	34	175	71	35
	20%	65	47	63	57	58	28	119	48	24	170	64	26
	10%	60	42	50	55	55	22	115	44	18	169	60	21
Far	no screen	259	343	1332	230	332	517	202	286	451	287	314	431
	90%	105	118	316	92	121	147	111	98	128	225	116	122
	80%	92	103	252	82	103	126	107	86	109	216	102	102
	70%	80	86	205	74	88	100	101	71	86	209	86	82
	60%	72	70	157	66	74	79	97	60	68	161	73	64
	50%	69	67	150	64	70	72	97	58	63	203	72	61
	40%	54	45	82	51	51	42	90	40	36	196	50	35
	30%	48	35	58	46	41	31	87	33	27	191	44	26
	20%	42	28	37	42	34	18	85	27	16	189	37	17
	10%	40	23	27	40	30	12	83	24	11	187	32	12

Table 7: Minimum recommended perforation rate to achieve target illuminance in all studied cases and zones. Lighter shade specifies higher perforation rate.

Minimum Perforation Rate													
Orientation		Summer			Autumn			Winter			Spring		
		7	09:30	12	7	09:30	12	7	09:30	12	7	09:30	12
Near	N			70									
	E	70		80	60			60			50		
	S			80					90	80			
	W			70									
Mid	N			90									
	E	50	80	90	50	70		90	90		50	70	
	S			90					70	60			80
	W			80									
Far	N												
	E	50	70		60	70			80		90	60	
	S			90			90		60	50		80	70
	W			90									

All screens on the West and North orientations reduced the illuminance sharply since there is no direct sun (Table 5&6), considering the fact that simulation times did not include afternoon hours when the direct Sun hits western façade.

The results also show that some cases provide average illuminance of more than 1200 lx without knowing if the area is considered as 'Overlit' or 'Daylit', which explains the necessity for the next phase to clearly understand the situation, using 'Daylight Availability' one of the Dynamic Daylight Performance Metrics "DDPM".

PHASE II: DAYLIGHT AVAILABILITY

In this stage, the daylight availability distribution is analyzed to compare the "no screen" case with different cases of perforation rates in the four main orientations.

Each one of the 345 measuring point presents a square with a color scale according to the percentage of the occupied hours that achieve the required threshold. The higher the percentage the lighter the square is. Each table represents one orientation, a plan of each case is presented and the total area of the plan is divided into three areas: 'Daylit', 'Partlylit' and 'Overlit'. Finally, the percentage of each area to the total space is presented in charts to compare cases for each orientations.

RESULTS OF PHASE II

The results show a linear increase of the 'Partlylit' area and decrease of the 'Overlit' area for East and South orientations when decreasing the perforation rate (Fig. 4,5). It appears that 'Overlit' area is reduced in all orientations with the use of solar screens, which means using solar screens would reduce direct sunlight penetration.

For the East orientation, 80% perforation rate achieves more 'Daylit' area than other rates in the East orientation, 90% & 70% perforation rates also provide acceptable 'Daylit' area of about 60% of total area (Fig. 4) and (Table 8).

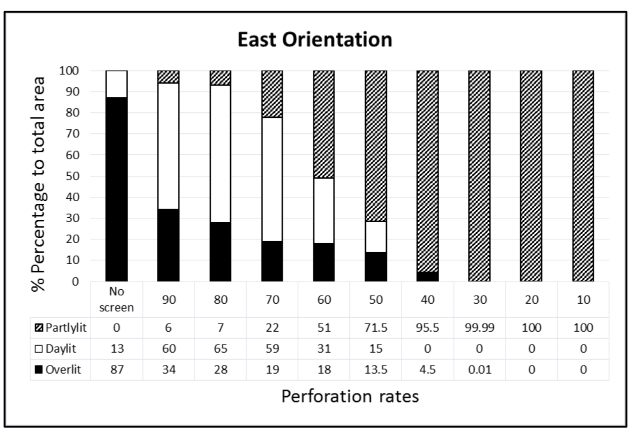


Figure 4: Daylight availability distribution relative to total area for the East orientation.

In the South Orientation, 90% perforation rate achieves better daylight availability than other rates, 70% perforation rate also achieves acceptable result of 41.5% 'Daylit' area of the total area (Fig. 5) and (Table 9).

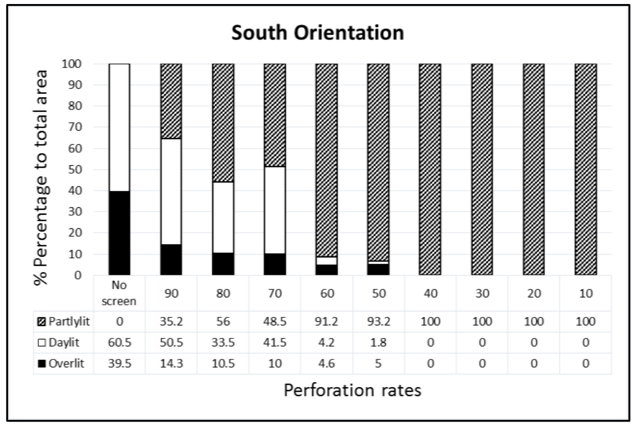
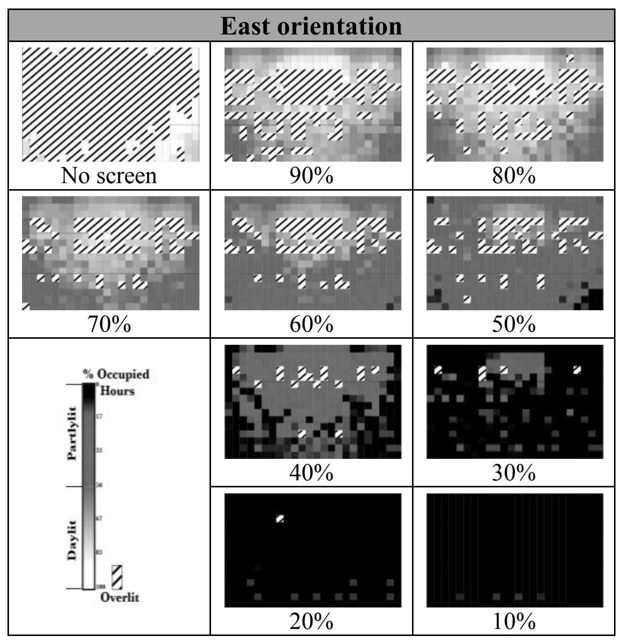


Figure 5: Daylight availability distribution relative to total area for the South orientation.

Table 8: Daylight Availability distribution on the classroom plan for each case on Eastern orientation.



For the North and West orientation, there were no issues of 'Overlit' spaces since there is no direct sunlight, however, all screens have sharply reduced the daylight availability, and all cases fail to achieve acceptable 'Daylit' area. Even 90% rate barely achieves 3% 'Daylit' area in North and 4% in West. (Table 10) shows a comparison between the 'no screen' case and 90% rate case; the transition between the two cases is not gradual like it is found in East and South orientations.

Table 9: Daylight Availability distribution for each case on Southern orientation.

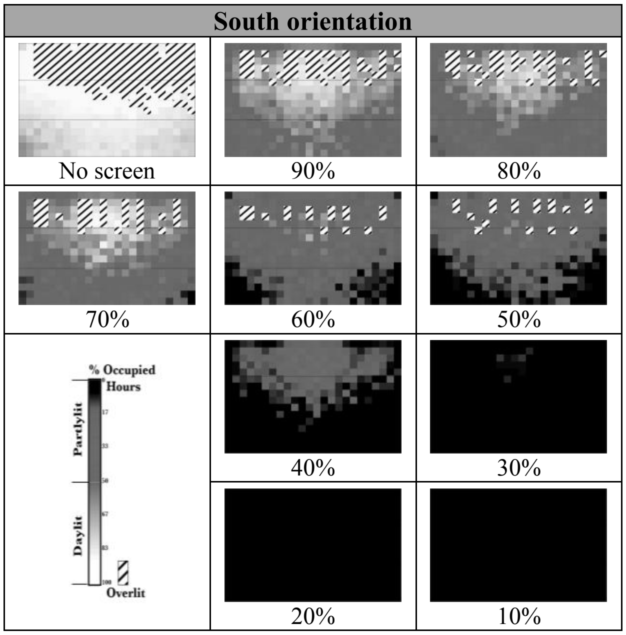
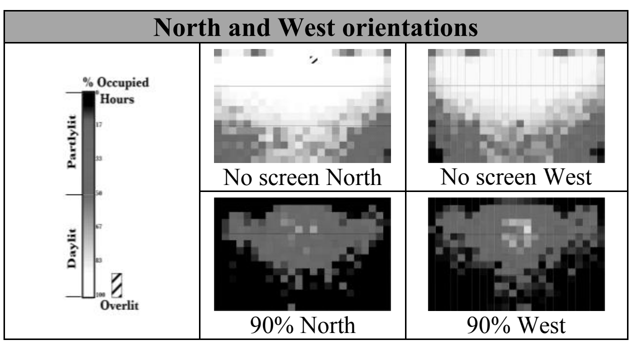


Table 10: Daylight Availability distribution for No screen and 90% cases on North and West orientations.



DISCUSSION

The simulation of a range of perforation rates for a solar screen demonstrates that the perforation rate is related to the orientation of the window and the time of the day. In the East and South orientations, there is a linear reduction of Overlit area with the use of solar screens. In the west orientation however, there are no Overlit areas as would be expected especially in summer, which is explained by the fact that the school day in this context finishes at 12:30 before the direct sun can hit the western façade. The results indicate that 70%, 80% and 90% perforation rate would achieve acceptable 'Daylit' area in the East orientation, and 90% & 70% in the South orientations. However, there is no evidence on which perforation could maintain privacy in classrooms; further investigation is needed to test the effect of perforation rate on maintaining privacy of schools occupants.

In the West and North orientations, there was a dramatic reduction of 'Daylit' areas between the 'no screen' case and the 90% rate screen. Other parameters could be the reason for that gap, for example, using less depth ratio 'module size / depth of screen' could provide better daylight for a screen with the same perforation rate. Hence, further investigation is needed for other parameters such as depth ratio, aspect ratio, cell size and axial rotation.

CONCLUSION

In conclusion, the result of this experiment provides a table (Table 5) that could be used as a tool to help architects to decide minimum perforation rate needed for different orientation and times for school classrooms in similar spaces at the same context. Moreover, (Fig. 4&5) would be useful to help architects to choose a perforation rate for solar screens according to the required percentage of 'Daylit' area to achieve illuminance level of 300 lux.

ACKNOWLEDGEMENTS

This research is supported by a scholarship from King Saud University. I thank the Saudi Deputy Minister of Education for valuable help in collecting preliminary data. I also thank Jakubiec, A., Reinhart, C., Hosney, A. and Fathy, F. for their help in DIVA and Grasshopper software use.

REFERENCES

1. Julian, W., (2006). *Lighting: Basic Concepts*. 6th Edition (Rev) ed. Sydney: USYD.
2. Sabry, H., A. Sherif and T. Rakha, (2011). Daylighting Efficiency of External Perforated Solar Screens: Effect of Screen Axial Rotation under Clear Skies. In *International Conference on Sustainable Design and Construction (ICSDC).* Kansas City, Missouri, March 23-25.
3. Fathy, H., (1986). *Natural energy and Vernacular architecture: principles and examples with reference to hot arid climate*. Chicago: University of Chicago.
4. Alitany, A., (2014*).* A new strategy of ICT integrated methodologies for 3D documentation : a case study of the projected wooden windows (The Roshans) in the historical city of Jeddah *(Saudi Arabia). Departament d'Expressió Gràfica Arquitectònica*. Barcelona, Spain, Universitat Politècnica de Catalunya.
5. Veitch, J., (2005). Light, lighting, and health: issues for consideration. *LEUKOS,* 2(2): p. 85-96.
6. Webb, A., (2006). Considerations for lighting in the built environment: Non-visual effects of light. *Energy and Buildings,* 38(7): p. 721-727.

7. Sabry, H., et al., (2014). Balancing the daylighting and energy performance of solar screens in residential desert buildings: Examination of screen axial rotation and opening aspect ratio. *Solar Energy,* 103: p. 364-377.
8. Sherif, A., H. Sabry and T. Rakha, (2010). Daylighting for privacy: evaluating external perforated solar screens in desert clear sky conditions. In *Renewable Energy*. Yokohama, Japan, June 27 – July 2.
9. Jakubiec, J. A. and C. F. Reinhart, (2011). DIVA 2.0: Integrating daylight and thermal simulations using Rhinoceros 3D, Daysim and EnergyPlus. In *Building Simulation-12th Conference of International Building Performance Simulation Association*. Sydney, November 14-16.
10. Reinhart, C. F. and O. Walkenhorst, (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings,* 33(7): p. 683-697.
11. Reinhart, C. F., et al., (2011). Diva for Rhino Ver. 2.0. [Online], Available: www.diva-for-rhino.com [10 October 2015].
12. Reinhart, C. and A. Fitz, (2006). Findings from a survey on the current use of daylight simulations in building design. *Energy and Buildings,* 38(7) : p. 824-835.
13. Mardaljevic, J., (1995). Validation of a lighting simulation program under real sky conditions. *Lighting Research and Technology,* 27(4): p. 181-188.
14. Reinhart, C. F. and S. Herkel, (2000). The simulation of annual daylight illuminance distributions: a state-of-the-art comparison of six RADIANCE-based methods. *Energy and Buildings,* 32(2): p. 167-187.
15. Reinhart, C., J. Mardaljevic and Z. Rogers, (2006). Dynamic Daylight Performance Metrics for Sustainable Building Design. *LEUKOS* 3(1): p. 24.
16. Reinhart, C. and P. Breton, (2009). Experimental Validation of Autodesk® 3ds Max® Design 2009 and Daysim 3.0. *LEUKOS,* 6(1): p. 7-35.
17. Rutten, D. and R. McNeel, (2012). Grasshopper. *Generative modeling for Rhino*. [Online], Available: www.grasshopper3d.com [29 October 2015].
18. Erlendsson, Ö., (2014). Daylight Optimization-A Parametric Study of Atrium Design: Early Stage Design Guidelines of Atria for Optimization of Daylight Autonomy. *School of Architecture and the built environmnet* Stockholm, Royal Institute of Technology. 111.
19. Lagios, K., J. Niemasz and C. Reinhart, (2010). Animated building performance simulation (abps)-linking rhinoceros/grasshopper with radiance/daysim. In *SimBuild*, New York, NY, August 11-13.
20. DOE., (2015). *Weather data file for Riyadh Saudi Arabia* [*online*]: U.S Department of Energy. Available: http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=2_asia_wmo_region_2/country=SAU/cname=Saudi%20Arabia [14 October 2015].
21. Hall, I. J., et al., (1978). Generation of a typical meteorological year. San Diego, CA, Sandia Labs., Albuquerque, NM (USA).
22. Alshaibani, K., (2015). Planning for Daylight in Sunny Regions. *In International Conference on Environment And Civil Engineering (ICEACE'2015*), Pattaya, Thailand, August 8-9.
23. IES, D., (2012). Approved Methods: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE).
24. Reinhart, C. and J. Wienold, (2011). The daylighting dashboard – A simulation-based design analysis for daylit spaces. *Building and Environment,* 46(2): p. 386-396.
25. Sherif, A., H. Sabry and T. Rakha, (2012). External perforated Solar Screens for daylighting in residential desert buildings: Identification of minimum perforation percentages. *Solar Energy,* 86(6): p. 1929-1940.
26. Kotbi, A. and E. Ampatzi, (2016). Using Mashrabiya to Enhance Daylight and maintain privacy in Girls' Schools in Saudi Arabia. In *9th conference of Saudi Students in UK*, Birmingham UK, Scientific Society for Saudi Students in UK, February 13-14.
27. Nabil, A. and J. Mardaljevic, (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings,* 38(7): p. 905-913.
28. BSI, B. E., (2007). 15251, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. London, UK, British Standards Institution.
29. Phillips, D. (2000). *Lighting modern buildings.* Oxford: Architectural Press.
30. Heschong, L. and H. M. Group (2012). Daylight Metrics. *PIER Daylighting Plus Research Program*. California, California Energy Commission.