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Evaluation of Lighting Conditions in Portable Classrooms and Analysis for Alternative Daylighting Systems

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Evaluation of Lighting Conditions in Portable Classrooms and Analysis for Alternative Daylighting Systems

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Abstract

Evaluation of Lighting Conditions in Portable Classrooms and Daylighting Analysis for Alternative Design

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Lighting conditions in multiple classrooms in central Texas were assessed, and the feasibility of improving portable classroom daylighting via alternative daylighting systems was also evaluated. Results indicate that surveyed portable classrooms generally provide sufficient levels of light with artificial lighting systems, but have less uniform lighting distribution than permanent classrooms. To evaluate the daylight availability in portable classrooms, a model was developed and verified using field data. Climate-based daylighting simulation was performed using DIVA for Rhino, which uses Radiance and DAYSIM as simulation engines. Results from the annual daylighting analysis suggest that limited amounts of daylight were available in portable classrooms over the course of a year. In order to assess the feasibility of improving portable classroom daylighting conditions, parametric studies were completed to investigate how different factors affect the levels of light in classrooms. Simulation results suggest that increasing window area and higher window placement allow more light into the classroom. Different external shading systems also affect the indoor daylight level. However, the impact of other

factors, including building orientation, ceiling-to-floor height, and classroom length-to-width ratio is minimal. While changing the window systems for an existing portable building can require a large construction effort and financial commitment, retrofitting with tubular skylights is a more approachable option. Daylighting analysis shows eight 356-mm (14-inch) diameter tubular skylights can provide the portable classroom with a sufficient light level for more than 60% of occupied hours. When daylighting alone cannot provide sufficient light, lighting control will successfully combine a daylighting system and an artificial lighting system to provide an adequate lighting environment.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

There were 98,328 public schools in the U.S. in 2011-2012, where students spend an average of about 7 hours per school day [1,2]. Considering the amount of time that students spend in classrooms every day, it is important to ensure good lighting conditions in those classrooms. Useful light can be provided by either natural light, artificial light, or a combination of both. Previous studies show that natural light not only provides high quality light, but also has benefits for students' health and academic performance [3,4].

Portable buildings are commonly used in U.S. public schools. In the 2012-2013 school year, 24% of public secondary schools had portable buildings [5]. Among public secondary schools, 43% of the portable classrooms were classified as being in fair condition, and 7% of the portable classrooms were in poor condition [5]. The indoor environmental quality in portable buildings, such as lighting, heating, cooling and noise control, are mostly rated lower compared to permanent buildings. Among secondary schools with portable buildings, artificial lighting is rated as unsatisfactory or very unsatisfactory in 12% of the schools, and natural lighting is rated as unsatisfactory or very unsatisfactory in 28% of the schools [5]. Concurrently, the percentage of schools with unsatisfactory or very unsatisfactory artificial lighting and natural lighting in permanent buildings are 7% and 16%, respectively.

Lighting systems in classrooms should provide adequate light for class activities, such as reading and writing. A majority of classrooms have windows, and the lighting system consists of a combination of artificial light and natural light. However, some classrooms have no windows, and the lighting source is limited only to artificial light. Both the quantity and quality of light in classrooms are important for the visual comfort and academic performance of students. Precedent studies on daylighting in school buildings have shown that daylight has significant benefits for students' health, class attendance and academic achievement [3]. Lighting conditions can also have a large impact on attendance rate [4]. Besides the psychological and physiological benefits from natural lighting systems, school buildings utilizing daylight also results in energy savings and reduced utility costs.

As natural light has benefits for students' health and academic achievement and can offset energy use, it is recommended to have both a daylighting system and an artificial lighting system in classrooms. A daylighting system can either work in parallel with an artificial lighting system or control the artificial lighting systems, either of which will effectively reduce energy consumption for electrical lighting. There are many published studies on predicting daylighting and improving daylighting control, but past studies have focused on office buildings. Daylight control can effectively regulate the indoor lighting condition and reduce electric energy use [6]. Further, advanced lighting control can also reduce operation costs of buildings and improve occupants' visual comfort in a cost effective way [7].

Daylight has potential to reduce the peak electrical demands and energy consumption related to space cooling. Li *et al.* [7] conducted field measurements on daylight control in several cellular offices in a particular office building in Hong Kong [7]. Results showed that with daylight controls an annual electric energy saving of 15.7 kWh/m^2 can be achieved compared to conditions without daylight control [7]. Yang *et al.* [8] investigated the economic benefits of using daylight control in office buildings. They showed that a daylight-linked lighting control system can effectively reduce energy use by an average of 30.5% compared to the base case for which no light control is applied [8].

While previous researchers have evaluated daylighting metrics, the benefits of daylight on students' health and performance, and the feasibility of using daylighting control in office space, there is no reported study of the light conditions in portable classrooms in U.S. In addition, the U.S. Department of Education's surveys on lighting condition rated portable classrooms lower than permanent classrooms [5]. Because portable classrooms have the same occupancy and class activities as those in permanent classrooms, it is important to improve the lighting conditions and provide the same level of visual comfort in portable classrooms as in permanent classrooms.

To evaluate the environmental conditions in regular and portable classrooms, a field study was performed in selected high schools in central Texas [9]. In this paper, we report on results for current lighting conditions in portable classrooms and the feasibility of utilizing natural light in those classrooms. Specifically a methodology for evaluating daylighting conditions in portable classrooms based on published studies on daylight metrics and daylighting simulations is presented. We then present and discuss the current lighting condition in portable classrooms that were studied, and compare the results with lighting standards. Simulation methods are used to conduct parametric analyses for optimizing daylighting conditions, and to develop new design and retrofit strategies that may improve daylighting conditions in portable classrooms.

Chapter 2: Review of Existing Daylight Metrics

A designer for the lighting system needs to know how to evaluate the quantity and quality of light and how to bring an adequate amount of light into the space by orienting and designing the structure properly. A good daylighting design provides the space with sufficient natural light while ensuring the space is free of any glare issues. Various daylight metrics are available for evaluating the quantity and quality of daylight in an enclosed space, and many studies validate and compare various daylight metrics.

Natural light that enters an interior space is not only direct sunlight but also diffuse sunlight, diffuse light from the sky, and diffuse light from the ground [10]. These light sources depend on multiple factors, including cloud cover and position of the sun. The illuminance distribution of the sky depends on latitude, climate, weather, and time of day. Since the sky conditions significantly affect the amount of daylight that is available to an indoor environment, daylight metrics are calculated under multiple sky conditions. Commission Internationale de I'Eclairage (CIE) developed 15 sky models ranging from overcast sky to clear sky [11]. Among the 15 standard skies, CIE Standard Overcast Sky and CIE Clear Sky are two particular sky conditions that are commonly used in light analyses to define an appropriate range of natural lighting conditions.

DAYLIGHT METRICS

Daylight illuminance is the basic daylight metric used for assessing the quantity of daylight. In classrooms, major activities involve reading and writing at desks. Thus illuminance is measured on the desk surface, typically around 0.8 m above the ground.

Daylight Factor (DF) measures the relative internal illuminance compared to that of the outside illuminance level under a standard overcast sky condition [12]. It is a relatively simple metric that assesses the quantity of daylight in a room. However, it has a few limitations. DF only roughly estimates the amount of available daylight under the overcast sky condition. Because direct sunlight is not included in the calculation [12,13], the effect of location and building orientation cannot be evaluated, and daylight glare cannot be detected using the daylight factor. In addition, because DF does not take into account the variation of the sky condition over time, the DF metric is limited to static analysis [13].

Daylight illuminance and Daylight Factor are static metrics that do not show the variation of light level over time. Climate-based daylight metrics have been proposed to evaluate the dynamic daylight condition, specifically Useful Daylight Illuminance (UDI) and Daylight Autonomy (DA). Useful Daylight Illuminance (UDI), defined as the light levels in the range of 100 – 2000 lux, was proposed in 2005 to evaluate the quality of the daylight based on work plane illuminances [13,14]. UDI evaluates the daylight that can be utilized for normal activities. The lower threshold is agreed to be 100 lux, while the upper threshold is still debated, but is most likely within the range of 2000 – 2500 lux [12]. When the illuminance level exceeds the upper threshold, it is likely that visual discomfort, such as glare, will occur. Table 1 shows the metrics used for determining daylight level using UDI [12,13]. While UDI are absolute values for illuminance, DA evaluates the frequency of meeting minimum lighting requirement.

UDI can be used to assess the quality of light available in a classroom. A well-designed classroom can provide UDI supplementary or UDI autonomous during a large percentage of occupied time during the day. Achieved UDI, defined as the percentage of the occupied time of the year when UDI is achieved, can be a representative value for the available amount of useful daylight [14]. A higher achieved UDI indicates that the classroom receives more useful light over a course of a year; it confirms that the classroom has a greater potential to utilize natural light and reduce the use of artificial lighting systems.

Illuminance	Daylight level	Abbreviation
<100 lux	UDI 'fell short'	UDI-f
100 – 500 lux	UDI supplementary	UDI-s
500 – 2000 lux (or maybe 500 – 2500 lux)	UDI autonomous	UDI-a
>2000 lux (or maybe >2500 lux)	UDI exceeded	UDI-e

Table 1: Determining Daylight Level Using UDI [12,13]

Five available daylight metrics are listed in Table 2. In this study, daylight illuminance, UDI, and DGP are used for assessing the daylighting conditions in portable classrooms, because daylight illuminance estimates the amount of light, UDI evaluates the availability of useful daylight, and DGP predicts glare issues. DF is not used because it cannot provide insights on lighting conditions under clear sky when direct sunlight is present. DA was not used because it evaluates the availability of daylight only based on the minimum requirement, and does not consider the upper threshold of useful daylight.

Daylight Metrics	Definition	Advantages	Disadvantages
Daylight Illuminance [lux, foot candle]	Amount of daylight that reaches a unit area on a surface	Measured using a light meter or light sensor	Point-in-time value
Daylight Factor (DF)	Ratio of internal illuminance to unobstructed horizontal illuminance under standard CIE overcast sky condition [12]	Simple concept; easily communicated with the design team.	Direct sunlight is not included in calculation; cannot be used to detect glare issues; building location and orientation are not taken into account
Useful Daylight Illuminance (UDI)	100 – 2000 lux, measured on a work plane [14]; Results are presented as the percentages of the occupied time of the year when UDI is achieved and not achieved [13]; Achieved UDI is the annual occurrence of UDI across the work plane [14]	Evaluates the availability of useful daylight; Is based on absolute values for illuminance; As a climate-based metric, UDI accounts for the variation of sky conditions over time [14]	
Daylight Autonomy (DA) (also called as Daylight Availability Ratio, DAR [15])	Percentage of the occupied times of the year when a minimum illuminance threshold is met by daylit alone [13,16]	Evaluates the availability of daylight; Indicates how frequent the minimum illuminance requirement is met by daylit alone; Climate-based daylight metric	Cannot detect if the space is overlit
Daylight Glare Probability (DGP)	Probability of daylight discomfort, in a range between 0.184 and 1 [17]; DGP<0.3: imperceptible glare DGP>0.45: intolerable glare	Based on contrast and total vertical eye illuminance; Considers vertical eye illuminance, source luminance and size, source luminance, and position of the glare source [17]	Cannot detect veiling glare

Table 2: A summary of daylight metrics.

Chapter 3: Methodology

The first part of this section describes field measurements, and the second part describes modeling and corresponding numerical analysis. The methodology for field measurements provides specifics related to the fieldwork and techniques used for collecting data from classrooms as well as information related to the processing of field data. The analysis sections include the setup of the baseline model and the metrics used for parametric analysis of multiple design schemes.

FIELD MEASUREMENT

In the spring of 2016, field measurements of lighting conditions in permanent and portable classrooms were completed in seven public high schools in central Texas. A total of 28 classrooms were surveyed for lighting conditions. Among the 28 classrooms, 21 classrooms were in permanent buildings and seven were in portable buildings [Figure 1]. Walk-throughs and measurements of light level were performed in the 28 classrooms over the course of two months. During each field measurement, instruments were set up in each classroom to record the variation of illuminance from Monday afternoon to Friday afternoon and point-in-time illuminance was measured in each surveyed classroom.

Among the seven portable classrooms, six were regular classrooms and one was a computer lab. Six of the seven classrooms had the same dimension; each of these classrooms was 9.8 m (32 ft) long and 7.0 m (23 ft) wide with a ceiling height of 2.3 m (7.5 ft). The other classroom was slightly larger, with a length of 11.0 m (36 ft), a width of 7.3 m (24 ft), and a floor-to-ceiling height of 2.2 m (7.5 ft). All portable classrooms had lay-in acoustic ceilings and carpet flooring. Each classroom had four 0.9 m by 0.9 m (3 ft by 3 ft) windows. All the windows were operable and double-hung with an aluminum frame and double-pane clear glazing. Among the seven portable classrooms, four had windows facing north and south, and three had windows facing east and west. Either a chalkboard, white board, or both were used in each classroom. The interior wall finish was either painted wood panels or a combination of wood panels and plaster finish.

Figure 1: Portable classroom (left) and permanent classroom (right).

Light data were collected using two types of instruments: a handheld light meter and a data logger with light sensor. The handheld light meter was used for measuring the point-in-time illuminance (lux) along the work plane. The light meter had a measurement range of 0 – 20,000 lux with an accuracy of ± 8 lux or ± 5% of the reading. The data logger was used to record the variation of light level in each portable classroom in order to assess the usage of artificial lights and presence of natural light. The data loggers had a measurement range of 10 – 30,000 lux and was set-up in the classrooms to record light measurements every 30 seconds over four continuous school days. They were positioned on survey towers, which were normally located near the wall or corner to avoid interrupting regular class activities. The point-in-time illuminance in classrooms was measured under the same lighting condition as when the classrooms were occupied by teachers and students. It was typically observed in all surveyed portable classrooms that ceiling lights were switched on and blinds were closed. Measurements were taken at 24 nodes uniformly distributed across the classroom, 0.8 m above the floor. The distance between two nodes was 1.5 m (5 ft). The distance between the edge nodes and the walls was between 1.1 m (3.5 ft). and 1.2 m (4 ft).

The mean illuminance and uniformity of light distribution in each classroom was evaluated based on the collected data. The lighting condition in portable classrooms was compared with that in permanent classrooms. Measured light levels in the classrooms were also compared to the recommended light level in the Illuminating Engineering Society of North America (IESNA) Lighting Handbook [19].

The recommended light level in classrooms generally ranges from 300 – 500 lux depending on the tasks that are performed [18]. IESNA provides a list of recommended light levels for various activities in classrooms [19]. In general, for people under the age of 25, the majority of the activities performed in the classrooms requires a light level in the range of 25 – 500 lux. In regular classrooms, the recommended light level is 200 lux for basic paper tasks and 250 lux for reading and writing. For science labs, the bench area should have a light level of 250 lux and the demonstration area should have a light level of 500 lux. In computer labs, where students have dedicated VDT screens, the recommended illuminance level is 75 lux.

PARAMETRIC ANALYSIS

In order to improve the daylighting conditions in the portable classrooms, parametric studies were performed to obtain an in-depth understanding of the impact of each parameter. Dynamic daylighting simulation was chosen as the method for assessing the daylight performance. Dynamic daylighting simulations were performed using DIVA for Rhino, a daylighting analysis plug-in for Rhinoceros [20], to investigate how daylight metrics are affected by changing various parameters. Point-in-time daylight illuminance, UDI, and annual DGP are the daylight metrics that were evaluated. Based on the results, recommendations were made for improving daylighting systems in the portable classrooms.

The following sections discuss the methodology of this parametric study. The first section explains the assumptions and information used for constructing the baseline model, which reflects the existing daylighting condition in a surveyed portable classroom. The second section describes the metrics used to study how changing different parameters affect the daylighting condition in alternative designs.

Simulation method

Simulation methods can be divided to two types: static simulation methods and dynamic simulation methods. Dynamic daylighting simulation was chosen for this study because it accounts for variations of sky conditions. Daylight metrics used in dynamic modeling are UDI, DA, and DGP.

DIVA for Rhino is a daylighting analysis tool using Radiance and DAYSIM as simulation engines for climate-based daylighting calculations [13,20]. It performs hourly calculations based on input information, including location, weather data, material properties, and sky conditions. Daylighting condition can be evaluated under various CIE Standard sky models. Electrical lights can also be modeled in DIVA to perform more comprehensive studies. The simulation engine, DAYSIM, uses the Dynamic Daylighting Simulation (DDS) model proposed by Bourgeois *et al*. [10]. In the DDS model, multiple light sources are considered, including diffuse contribution from the sky and ground and direct and indirect solar contributions [10]. Each of the light sources is counted separately in the model. The sky is divided into 145 diffuse sky segments for calculating diffuse sky contribution [10]. A total of 145 indirect solar positions are used for calculating the solar ray reflected off surfaces, and 2305 direct solar positions are used for calculating the direct beam of sunlight [10].

Model description

The daylighting analysis model was developed based on the existing conditions observed and measured in one of the surveyed portable classrooms. The classroom was modeled as 9.8 m × 7.0 m × 2.3 m (32 ft × 23 ft × 7.5 ft) with four double-hung windows of 0.9 m × 0.9 m (3 ft × 3 ft) and a sill height of 0.9 m (3 ft). The two sidewalls with windows were set to face north and south. Each of the sidewalls had two windows. The window frame was modeled with a reflectance of 0.7, and the glazing was modeled as double-pane clear glass with a light transmittance of 0.8. Venetian blinds were modeled on the interior side of the windows with a reflectance of 0.5. A door was located on the west end of the north-facing wall. A floor plan and prospective view of the modeled portable classroom are provided in Figure 2.

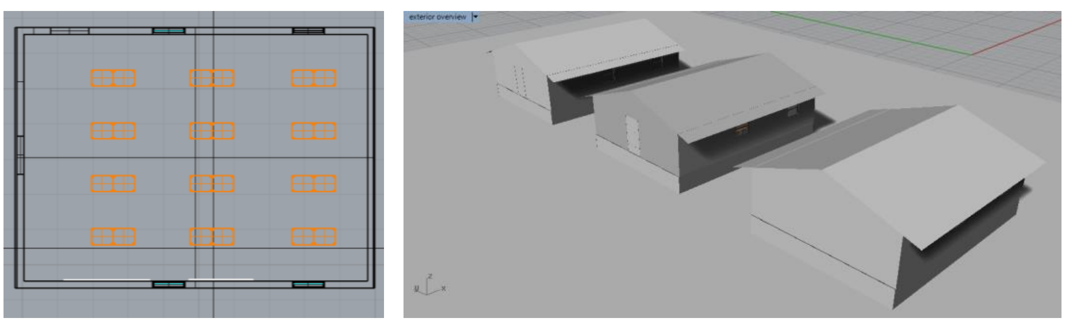


Figure 2: Floor plan (left) and exterior overview (right) of the portable classroom modeled using Rhino.

The room parameters and external conditions for the daylight illuminance analysis are summarized in Table 3. The key boundary conditions in the study were the sky condition, solar angle, and outdoor horizontal illuminance. These boundary conditions were defined by the actual date and time of measurements for the point-in-time illuminance calculation and by the TMY3 weather data collected at Austin Mueller Airport for the annual daylighting analysis. After the model was set up, mesh sensitivity was tested using different cell sizes. The daylight model was then validated using the three sets of measurements taken under a CIE standard clear sky. The first set of measurements were on March 19, 2016, conducted with the ceiling light on and with the blinds lowered at 13:30. The second set of measurements were on October 28, 2016, conducted with lights off and blinds up at 15:20. The third set of measurements were at 16:10 on October 28, 2016 under the same condition as the second set of measurements. Annual UDI and annual daylight glare probability were calculated for the existing condition to evaluate the availability of daylight in the classroom and the possibility of potential glare issues throughout the year.

External Conditions		
Weather and Location		Austin Mueller AP, Texas
Ground Reflectance		0.2
Roof Reflectance		0.35
Adjacent Building Surface Reflectance		0.35
Distance between Adjacent Portable Buildings		4.9 m (16 ft)
Room Parameters		
Classroom Length		9.8 m (32 ft)
Classroom Width		7.0 m (23 ft)
Ceiling Height		2.3 m (7.5 ft)
Orientation		North - South
Window	Type	Double-hung
	Size	0.9 m × 0.9 m (3 ft × 3 ft)
	Light transmittance	0.80 (double-pane clear glass)
Room Surface Reflectance	Ceiling	0.7
	Floor	0.2
	Interior wall – white/wood	0.4
	Door	0.4
	Window frame	0.7
	Venetian blinds	0.5
	Projector	0.4
	Student desk	0.5
	Chalkboard	0.4
	Whiteboard	0.5
Ceiling Light	Type	Recessed
	Amount of ceiling light	9
	Amount of lamps	2 lamps per ceiling light
	Lamp model	T8 fluorescent tube
	Power output	32 W

Table 3: Daylighting model input.

Metrics for parametric analysis

Existing portable classrooms are dominated by artificial lighting. Because the field study confirmed that classroom blinds are down almost all of the time, it is likely that there is insufficient useful daylight admitted into the existing portable classrooms. To develop strategies for improving daylighting conditions in the classrooms, metrics were developed to perform parametric analyses. The impacts on daylighting conditions by multiple parameters were explored. Parameters included orientation, classroom length-to-width ratio, ceiling height, window size and type, and external shading system. Alternative designs listed in Table 4 were investigated using the daylighting simulation tool, DIVA for Rhino. The availability of useful daylight over the course of a year was evaluated for each alternative design to assess the effectiveness of improving daylighting condition.

Parameter	Existing design	Alternative design
Orientation	N&S	W&E, NE&SW, NW&SE
Classroom footprint	7.0 m × 9.8 m (23 ft × 32 ft)	6.1 m × 11.3 m (20 ft × 37 ft), 7.9 m × 8.5 m (26 ft × 28 ft)
Ceiling height	2.3 m (7.5 ft)	2.4 m (8 ft), 2.6 m(8.5 ft), 2.7 m(9 ft)
Window design	Four 0.9 m × 0.9 m punch windows	(1) clerestory window of a height of 0.9 m (2) strip window of a height of 0.9 m and a sill height of 0.9 m
External shading system	Eave overhang	(1) Fixed horizontal louver on the exterior side (2) Light shelf on the exterior side (3) No shading

Table 4: Metrics for daylighting parametric analysis.

Daylight availability analysis

In order to assess the possibility of using daylight only in the classroom, the accessibility to sufficient daylight at different locations in the classroom was evaluated. Hourly illuminance level over the course of a year at each calculation node was calculated by DIVA. The percentage of nodes that have illuminance in the range of 100 - 2000 lux was calculated at each occupied hour. The number of hours and the percentage of occupied time at which at least 95% of the nodes had an illuminance of 100 – 2000 lux were calculated. When more than 95% of the area received useful daylight, daylight was considered sufficient for illuminating the classroom. In addition, the percentage of occupied time during which at least 25%, 50%, and 75% of the nodes had an illuminance of 100 – 2000 lux was calculated and compared.

$$P_{nodes} = \frac{N(100\ lux \leq Ev \leq 2000\ lux)}{N} \tag{1}$$

where P_{nodes} = Percentage of nodes that had illuminance in the range of 100 – 2000 lux at a specific occupied hour

N (100 lux≤Ev≤2000 lux) = Number of nodes that had illuminance in the range of 100 – 2000 lux at a specific occupied hour

N = Total number of nodes in the classroom

$$P_{occ,x\%} = \frac{hr_{x\%}}{hr_{total}} \tag{2}$$

where $P_{occ,x\%}$ = Percentage of occupied time at which at least x% of area had useful daylight illuminance

$hr_{x\%}$ = number of hours that at lease x% of the nodes had useful daylight illuminance (100 – 2000 lux)

x% = 25%, 50%, 75%, 95%

hr_{total} = total number of occupied hours

Chapter 4: Results

Surveyed results for the mean illuminance and uniformity of light distribution in 28 classrooms are presented in this section. A discussion of lighting conditions in permanent versus portable classrooms is also provided. Field measurements and dynamic daylighting simulation results for alternative designs are compared, along with a discussion of the contribution of each factor to the availability of daylighting illuminance.

FIELD MEASUREMENT

Results from field measurements of light variation are presented in Figure 3. The stationary sensor randomly positioned in the classroom primarily measured temporal variation of the light in the room. A sharp change of the light levels in Figure 3 indicates that artificial lights were either turned on or turned off by the occupants. According to the school schedule, the first class begins at 9:00. As the graph indicates, artificial lights were turned on a few minutes before class started, some short breaks were taken during the day, and the teacher left from the classroom at approximately 18:00. Overall, the results indicate that the portable classroom is dominated by artificial light as there is no large variation of illuminance during the occupied time. This pattern was observed in all seven portable classrooms and in many permanent classrooms.

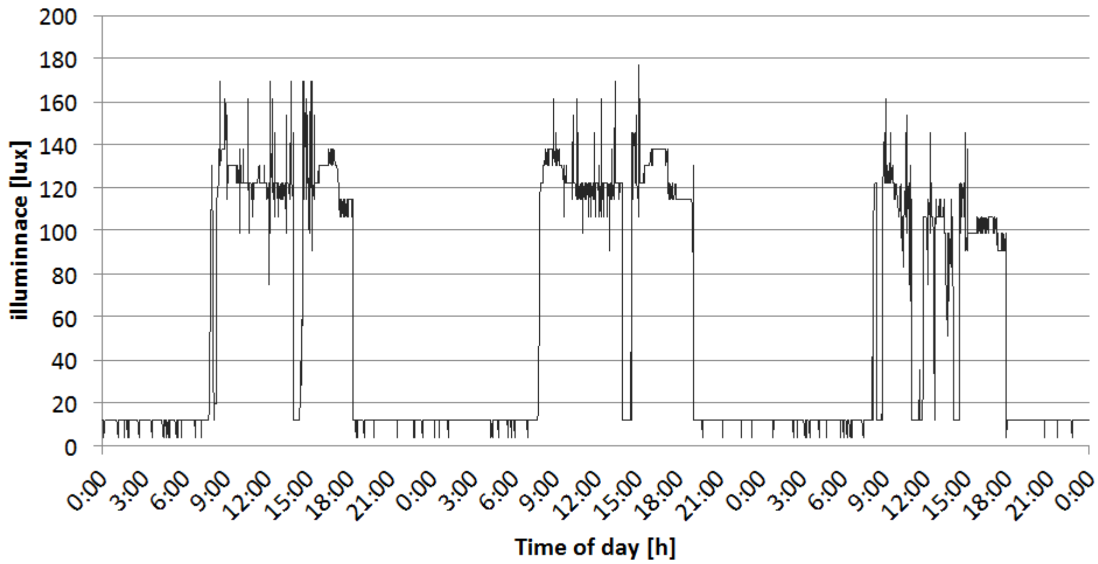


Figure 3. Continuous light level measured at a specific location in one portable classroom over three days.

Table 5 summarizes the illuminance data collected from seven portable classrooms at 30 horizontal locations in the occupied zone of each classroom at the desk height. Measurements were taken between 13:00 and 17:00. All measurements were taken on sunny days with less than 50% cloud cover. When the measurements were taken, the ceiling lights were turned on and blinds were put down, which was observed to be a regular practice in all portable classrooms. The average illuminance in portable classrooms ranged from 539-747 lux. The lowest illuminance was 136 lux, and the highest illuminance was 1310 lux. A large variation of light level was observed in each portable classroom. Correspondingly, the standard deviation and 95% confidence are relatively large. As the target light level in regular classrooms is 200 lux for basic paper tasks [19], the artificial lighting systems in portable classrooms generally provided the recommended amount of light. For each of the seven portable classrooms, less than 10%

of the measurements were below 200 lux. Therefore, the analyzed portable classrooms generally had sufficient light when the ceiling lights were on.

Room number	Mean (lux)	Min. (lux)	Max. (lux)	Percentage below 200 lux	Standard deviation (lux)	95% Confidence (lux)
P1	581	257	929	0%	227	91
P2	747	183	1310	4%	365	146
P3	539	210	1075	0%	180	64
P4	572	236	910	0%	178	64
P5	642	136	1180	4%	297	119
P6	600	190	940	4%	219	88
P7	594	125	1000	8%	249	100

Table 5: Light levels measured in portable classrooms.

Figure 4 summarizes the lighting conditions measured in 28 classrooms including portable and permanent classrooms. All the data were collected in the same lighting condition as when students and teachers occupied the classrooms. The mean light level in permanent classrooms had a wider distribution than that in the portable classrooms. One explanation for the large variation is that multiple types of classrooms were surveyed in this study, including computer labs, science labs, and regular classrooms. Computer labs generally require less light, while science labs require a higher light level. In addition, the surveyed permanent classrooms had different room geometries and different arrangements of electric lighting systems and windows. In contrast, all the surveyed portable classrooms had similar daylighting systems and electrical lighting systems.

Large variations of light levels were present in all portable classrooms and some permanent classrooms. Generally, the light level in portable classrooms had a larger standard deviation than that in permanent classrooms. This indicates that most of the permanent classrooms had more uniform light distribution compared to the portable classrooms. IESNA recommends 200 lux for basic paper tasks and, in general, a light level of 300 – 500 lux is recommended for the majority of activities performed in classrooms [19]. As shown in Figure 4, a large number of classrooms had more than sufficient light when they were occupied.

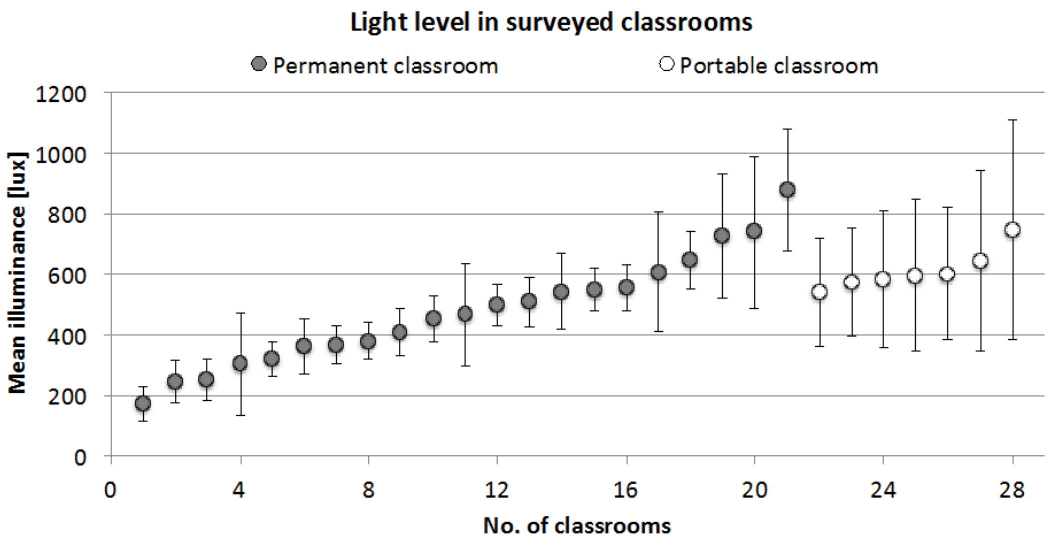


Figure 4: Mean illuminance and standard deviation in permanent and portable classrooms.

ANALYTICAL ANALYSIS USING DIVA

Based on general observations and field measurements in one of the surveyed portable classrooms, a lighting model was set up using Rhino and DIVA to represent the typical lighting environment in a portable classroom. Mesh sensitivity was tested and the DIVA model was verified using field measurements. The validated model was then used to evaluate the impact of multiple parameters and the feasibility of improving daylighting condition by modifying these parameters.

Mesh sensitivity

Mesh sensitivity was tested to decide the mesh size that produces results with both acceptable accuracy and low computational costs. Six mesh sizes were examined using the DIVA model. The six mesh sizes were used to calculate point-in-time illuminance at 9:00, 12:00, and 15:00 and percentage of space with $UDI_{100\text{-}2000\ lux}$ larger than 50% of occupied time. As shown in Table 6, the simulations using 3168 nodes and 792 nodes yielded close results. The comparison between 3168 nodes and 792 nodes provided a 2% difference in mean illuminance, 1% difference in standard deviation of indoor horizontal illuminance, and 0% difference in UDI. The mesh with 792 nodes (0.3 m×0.3 m cell size) was verified for grid independence and thus chosen for annual daylighting simulations and parametric analyses.

Grid independence was further verified using field data measured at 16:10 on October 28, 2016. Field measurements were taken at 30 evenly-distributed locations at 0.8 m above the floor. Illuminance level under the same sky condition and at the same solar time was calculated using a coarse mesh consisting of 30 nodes and a fine mesh consisting of 792 nodes. As shown in Figure 5, the finer mesh predicted better results and was more capable of capturing the point-in-time illuminance spikes than the coarse mesh.

	June 21, 9:00		June 21, 12:00		June 21, 15:00		Percentage of space with $UDI_{100\text{-}2000\ lux}$ larger than 50%
Mesh size	Mean Illuminance (lux)	Standard Deviation (lux)	Mean Illuminance (lux)	Standard Deviation (lux)	Mean Illuminance (lux)	Standard Deviation (lux)	
3168 nodes	58.6	65	80.5	99	62.5	71	23%
792 nodes	60.0	66	80.3	99	60.1	71	23%
391 nodes	59.7	64	78.3	94	63.4	68	24%
108 nodes	57.7	54	84.4	80	59.8	56	28%
48 nodes	54.2	44	77.8	60	57.4	47	25%
30 nodes	51.4	35	73.4	56	57.6	34	20%

Table 6: Mesh sensitivity test for DIVA model.

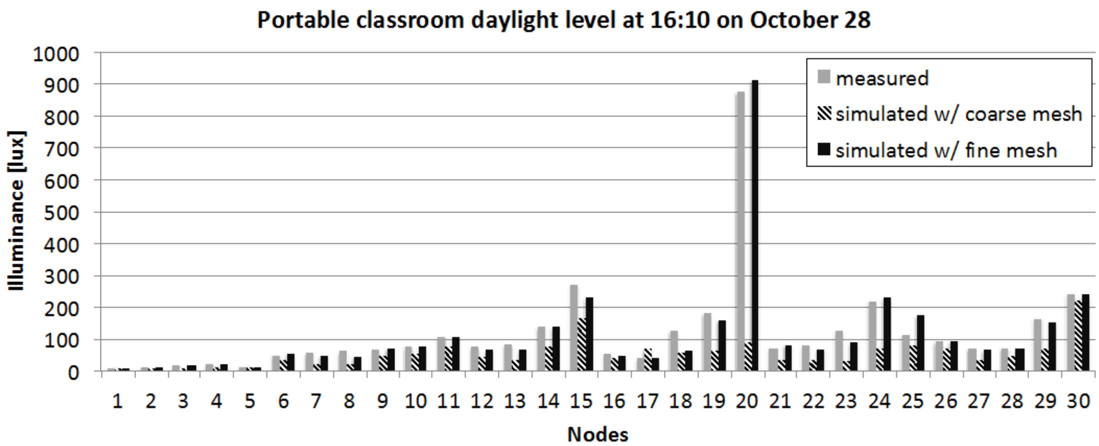


Figure 5: Comparison of illuminance calculated from coarse mesh and fine mesh with measured illuminance.

DIVA model validation

The following graphs [Figure 6 and Figure 7] compare the DIVA model with actual measurements taken with and without electric lights. By and large, the DIVA model captures the horizontal illuminance and variation of light level across the classroom. Because the simulation nodes are not at the exact locations where the measurements were taken (due to slight position variation during measurements), the model did not capture the illuminance spike. In addition, when light level is below 10 lux, the light meter may be incapable of capturing any light due to the light meter's accuracy of ± 8 lux.

Overall, the model appears reliable and for further daylighting analysis. Even though the simulation does not perfectly match the field measurements, it captures the trend of light distribution and variation. Further daylighting analyses used a dynamic daylighting method to evaluate the daylighting level over the course of a year.

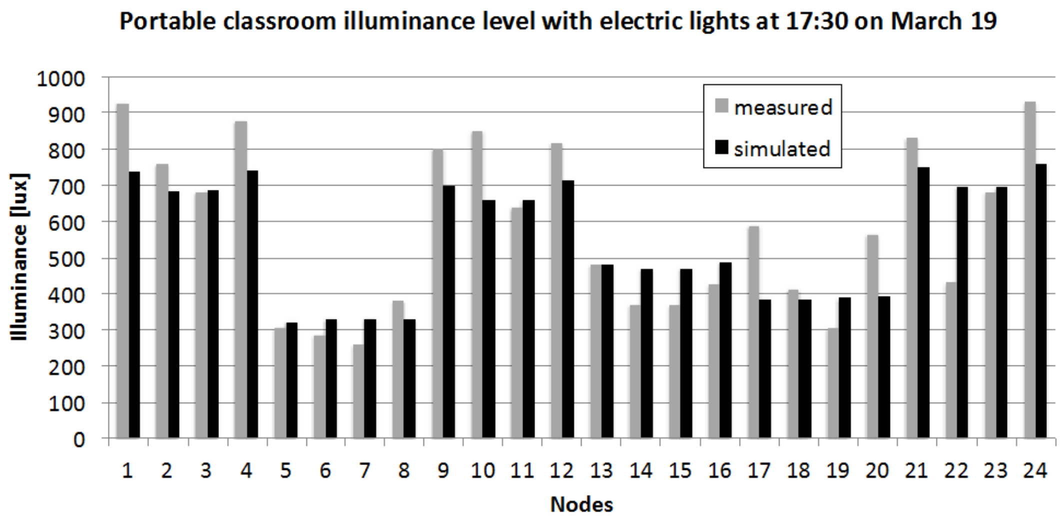
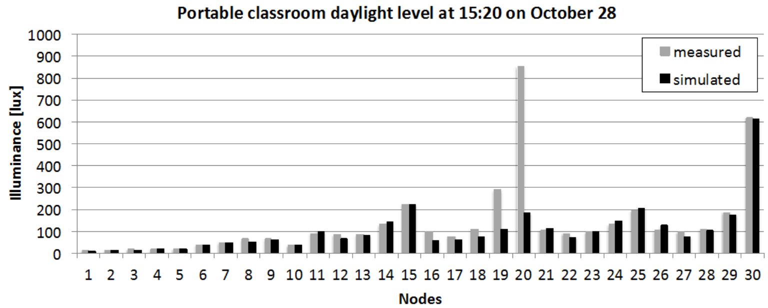
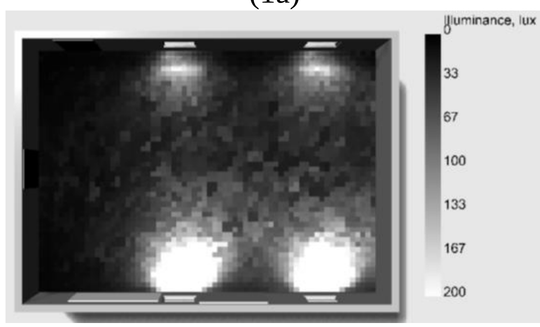


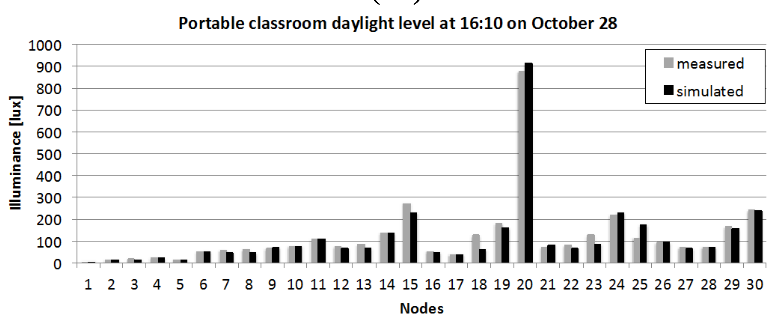
Figure 6: A comparison of simulated illuminance with the measured data at 17:30 on March 19, 2016.



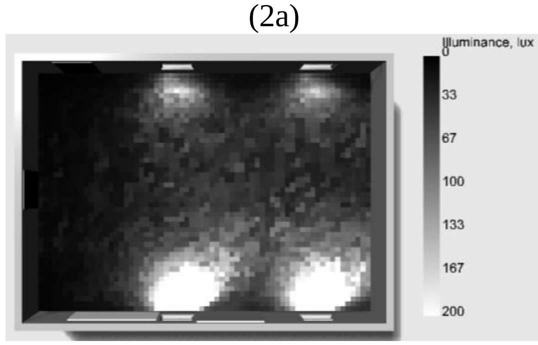
(1a)



(1b)



(2a)



(2b)

Figure 7: Comparison between DIVA model and actual measurement at 15:20 on October 28 (1a) and illustrations of light distribution in the classroom (1b); comparison between DIVA model and actual measurement at 16:10 on October 28 (2a) and illustrations of light distribution in the classroom (2b).

UDI analysis for existing condition

The annual UDI analysis shows that the model portable classroom does not have sufficient daylight all year round. For 55% of the occupied time, there is at least 25% of occupied area with useful daylight. When the occupied area with useful daylight is increased to 50%, the percentage of occupied time with this condition drops to 1%. Over the course of a year, the percentage of occupied area which has illuminance level in the range of 100 – 2000 lux never reaches 75% at any occupied hour.

Daylight Glare Index was calculated at one specific location to analyze the possibility of having glare issues in the classroom. The camera was positioned at approximately the eye level of a student sitting by the desk near the window, facing the wall opposite the teacher. Daylight Glare Probability (DGP) was less than 0.35 for the whole time. No disturbing or intolerant glare was detected.

Effect of room geometry

Figure 8 summarizes the simulation results for the availability of daylight considering classroom orientation, classroom length-to-width ratio, and classroom ceiling height. The details of the baseline model and the three considered variations are provided in the methodology section. Results show that changing the classroom orientation and length-to-width ratio barely improves the daylighting illuminance in the room. Orientating the walls with windows to face northeast and southwest only causes an increase of 1% in the percentage of occupied time with useful daylight covering more than 25% of occupied area. Increasing the length of the classroom by 1.5 m (5 ft) and reducing the width by 0.9 m (3 ft) does not have a significant impact either. Moreover, the availability of useful daylight was cut by nearly half when the length of the classroom was reduced by 1.2 m (4 ft) and the width was increased by 0.9 m (3 ft). Increasing the ceiling height had a slighly adverse impact on the availability of daylight. Overall, based on the UDI analysis, simply changing the room geometry did not significanly improve the availability of daylight in the classroom.

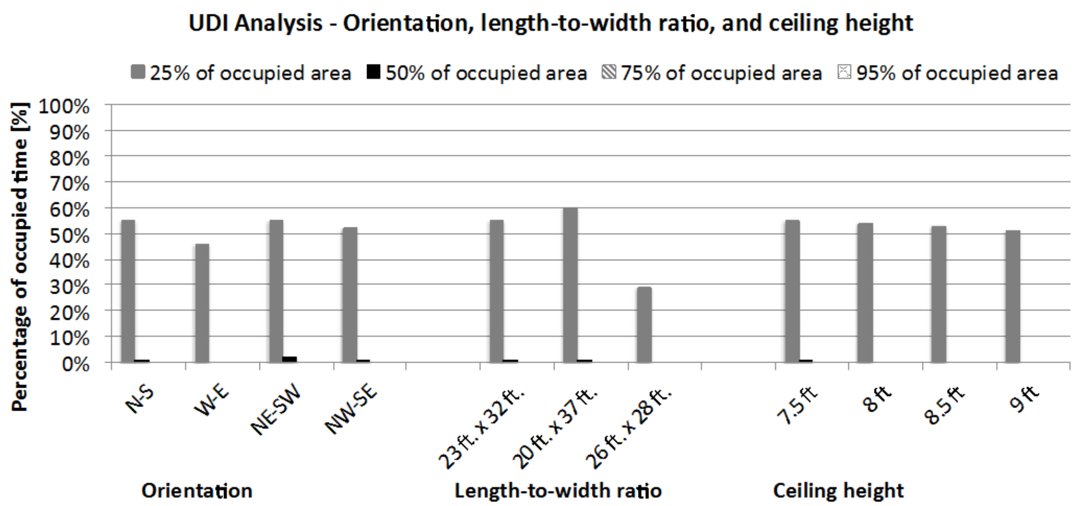


Figure 8: Daylight illuminance availability under different design alternatives.

Effect of alternative window systems and external shading systems

Three window systems were evaluated without the shading effect from the eave [Figure 9 (left)]. In the baseline case, the total window area was 3.3 m^2 (36 ft^2). The total window area in both the strip window case and clerestory window case was 14.5 m^2 (156 ft^2). The sill heights of the punch windows and strip windows were 0.9 m (3 ft) and the sill height of the clerestory window was 1.4 m (4.5 ft). Simulation has shown that a larger window area provides more light and higher window placement allows the sunlight to penetrate deeper into the classroom. Compared to punch windows, both strip windows and clerestory windows with larger window area significantly improved the availability of daylighting in the classroom. In addition, the clerestory windows also improved the light distribution in the room. In the strip window scheme, useful daylight was available to more than 75% of the occupied area for 88% of the occupied time and was available to more than 95% of the occupied area for 1% of the occupied time. In the clerestory scheme, for 92% of the occupied time, useful daylight was available to more than 75% of the occupied area; additionally, useful daylight was available to more than 95% of the occupied area for 26% of the occupied time.

Daylight illuminance availability when three different external shading systems were in use and when no external shading system was present were evaluated [Figure 9 (right)]. A horizontal louver had little effect on changing the daylighting condition in the classroom, only increasing the occupied time with 25% useful daylight by 4%. Using light shelves significantly improved the distribution of the daylight. Yet, the spatial availability of useful daylight never reached 75%. Furthermore, removing the eave results in similar daylighting availability as using light shelves.

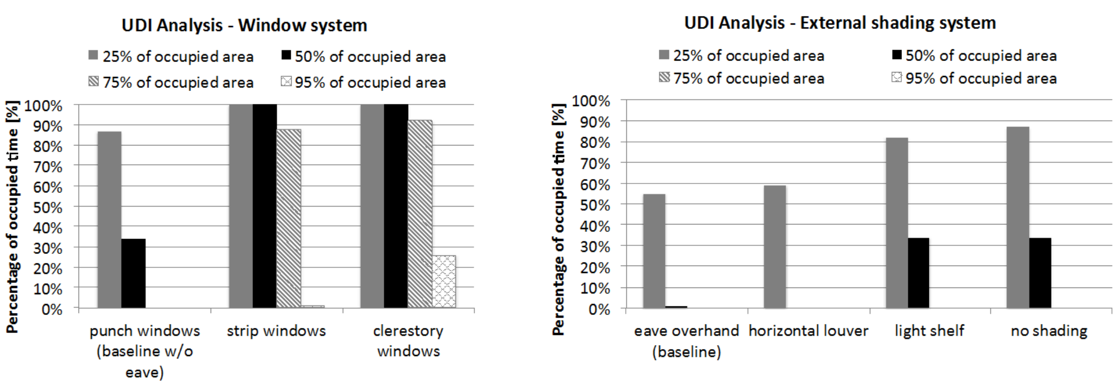


Figure 9: Comparisons of daylight illuminance availability for different window systems (left) and different external shading systems (right).

Existing classroom retrofit using tubular skylight

To examine the effectiveness of a tubular skylight, the annual availability of daylight in a classroom renovated with tubular skylight was calculated [Figure 10]. The tubular skylight was modeled as a Lambertian surface with no specular reflection. The effective light transmission was assumed to be 60% based on a previous study [21] and data sheets from multiple manufacturers. Two design schemes were evaluated, six evenly distributed 356-mm (14-in) diameter tubular skylights and eight evenly distributed 356-mm (14-in) diameter tubular skylights. Results show that the availability of useful daylight is significantly increased by having tubular skylights. In addition, the percentage of occupied time having useful daylight for at least 95% of occupied area, the threshold at which daylight alone is considered sufficient, was significantly increased by adding two more skylights. Comparing the daylighting availability between using tubular skylight systems and using a clerestory window system shows that the chance of achieving conditions where daylight alone is sufficient was more than doubled by using skylight system.

The average cost of a 356-mm diameter tubular skylight is in the range of $200 - $400. The installation cost varies from $200 to $400. The cost of installing eight skylights will range from $3200 to $6400. The electric consumption for operating the ceiling lights in the existing portable classroom is estimated to be 2300 kWh. The energy savings by using tubular skylights is approximately 1400 kWh. Based on the rate of $0.10 per kWh, the annual energy saving is around $140. Assuming no interest rate, the payback period for one portable classroom will be at least 23 years without considering other factors. However, this purely economic evaluation does not include benefits to students in terms of educational experience and performance.

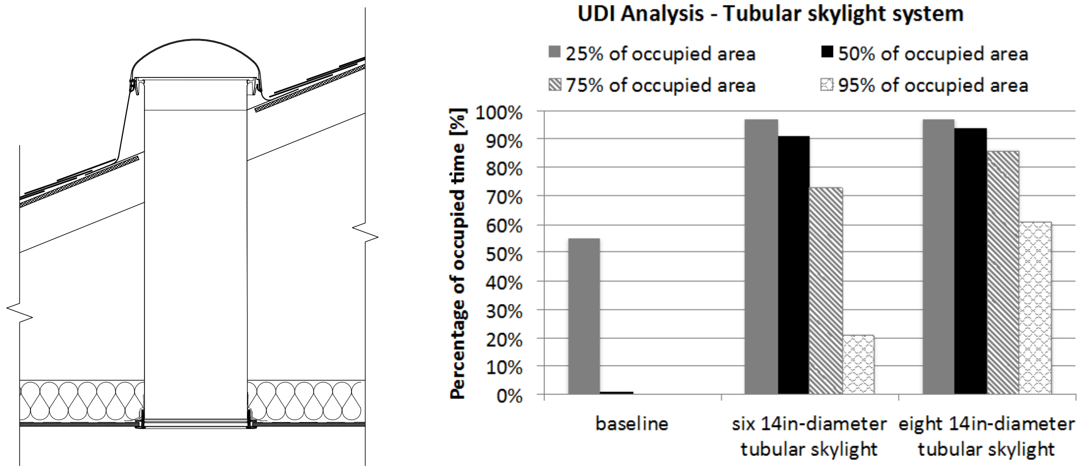


Figure 10: A section showing the tubular skylight system installed on the roof (left) and daylight illuminance availability after installing tubular skylight system (right).

Daylight glare analysis

UDI analysis suggests that portable classrooms renovated with clerestory windows or the tubular skylight system would have higher daylight illuminance and more uniform daylight distribution. In order to identify the possibility of having glare issues in the two alternative designs, DGP was calculated for these two schemes. A hypothetical camera was positioned at the same location with same angle and same depth as in the baseline case. In both cases, DGP was less than 0.35 for all calculated hours. No disturbing or intolerant glare was detected. However, this approach has limitations. In this analysis, only one interior view was assessed for glare probability. Because glare issues are complicated, DGP can vary significantly between different locations. In order to obtain a more comprehensive result, more locations should be selected to perform daylight glare analysis.

Chapter 5: Conclusion

Current lighting conditions in portable classrooms in central Texas were investigated. A comparison between permanent classrooms and portable classrooms indicates that the light distribution in portable classrooms was less uniform than in permanent classrooms. Parametric modeling study was used to investigate the effect of multiple parameters on daylight availability in portable classrooms. While other parameters have little impact on daylight availability, window area, window sill height and external shading were predicted to have a large impact on daylight illuminance in a model portable classroom. Daylighting conditions can be significantly improved by increasing the window area and window sill height. In addition, the feasibility of using an alternative daylighting system with tubular skylights was analyzed. Daylight availability improved significantly with the tubular skylight system. This finding suggests that it is feasible to renovate existing portable classrooms with tubular skylights to improve the daylighting condition.

While 95% of area with useful daylight can only be achieved for a percentage of the total occupied time, successfully using lighting control can improve the use of natural light. Daylighting can be combined with artificial lighting when natural light is not sufficient. This can be achieved by giving more flexibility to the artificial lighting system so that the daylighting system and artificial lighting system are used simultaneously. The flexibility of artificial lighting systems can be improved by using dimmable lights and multiple switches to control each row of ceiling lights separately.

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