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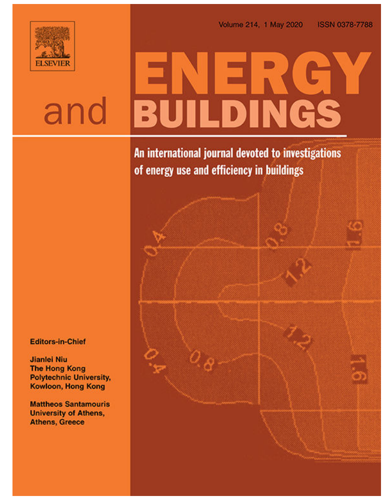

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Title Page

Questionnaires and simulations to assess daylighting in Italian university classrooms for IEQ and energy issues

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Abstract

Results from the DAYKE-Italy project are presented. An investigation on daylighting in eight classrooms in five Italian universities was carried out through a combined approach: an ad-hoc survey administered to students to investigate how they perceive daylight in classroom, and numerical simulations (DIVA+ALFA) to calculate a set of objective metrics (daylight, circadian, and energy-related). A sample of 542 questionnaires was collected through two sessions and the subjective judgments were correlated to objective metrics. Results from descriptive and statistical analyses showed: (i) the correlation was significant for all daylight metrics: among them, average daylight factor and annual light exposure performed higher correlations compared to daylight autonomy, spatial daylight autonomy and useful daylight illuminance; (ii) rooms with a scarce or an optimal daylight provision (according to standards) were rated with comparable subjective score; (iii) the equivalent melanopic lux showed a higher correlation than daylight metrics based on the horizontal workplane; (iv) energy saving up to 50% can be achieved in the presence of high daylight provision and through daylight responsive controls; however, a relamping of fluorescent systems with LED system is recommended to optimize the consumption; furthermore, estimated saving correlated significantly with objective metrics.

Keywords: DAYKE-Italy; DAYKE project; questionnaire survey; daylight in classrooms; daylight metrics; equivalent melanopic lux; statistical analyses.

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1. Introduction

Classrooms are acknowledged as spaces of primary importance for the learning activities that take place in them and that involve cognitive processes of students, whatever their age. In such spaces, daylighting plays a crucial role in occupants' health and well-being, to enhance indoor environmental quality and reduce energy consumption for electric lighting. Daylighting is beneficial to the occupants from several viewpoints. Firstly, it contributes to the aesthetical and physical character of a learning space, as well as to limit potential harmful effects due to prolonged exposure to electric lighting [1-5]. Secondly, it is strongly associated with the improvement of students' performance and health conditions [6-8]. Finally, an insufficient or lacking daylight provision may result in fatigue, stress, circadian dysfunction, phase shifting, and Seasonal Affective Disorder (SAD) [9-10].

A direct link between daylighting and student performance has been reported, as human health and mental functions are set by circadian rhythms, which are influenced by the duration and the intensity of light exposure during the day.

Furthermore, aspects such as daylight availability and distribution, presence of glare sources, direct sunlight penetration and view to the outside need to be accounted for to achieve visual comfort and optimize the use of electric lighting in an energy saving perspective [11-14]. Turning off electric lights when sufficient daylight is available can save a significant amount of lighting energy costs [15-16]. Cooling costs can also be reduced through appropriate daylight design [17-19].

In Italy, as well as in other European countries, it often happens that classrooms are hosted in buildings that were not conceived for the purpose. For instance, historic buildings are frequently turned into educational buildings, thus modifying their original function. This process of adaptive reusing is one method for preserving heritage buildings; however, sometimes this process penalizes the quality of daylight and the well-being of students [20]. It is quite difficult to reconcile the cultural value of historic buildings with daylighting standards for visual comfort and performance [21].

From a design viewpoint, nowadays designers and building practitioners need to deal with a quite complex body of regulations and recommendations on daylighting, which introduced a rich yet often non-homogenous set of daylight criteria and metrics. Legislations/regulations may differ, as well as reference criteria and requirements, depending on the specific country where designers operate. The complexity is even increased if non-legislative but largely used protocols for sustainable environmental-energy analyses (f.i. LEED, BREEAM) are considered as targets for the project [22-23]. Consequently, designers must refer to the traditional average daylight factor, still the reference metric in the legislation of many countries (including Italy), but also comply with requirements derived from the so-called climate-based daylight modeling. The design process appears more and more the result of a complex trade-off among different metrics and criteria (daylight and circadian), where the impact of the spectral distribution of both natural and electric light sources on the circadian rhythm also needs to be taken into account. A description of the most widespread daylight approaches (and relative metrics) is provided in Section 2.

Several studies have been conducted on the energy aspects of daylighting in schools or on the application of climate-based metrics to calculate the daylight provision in learning spaces [24-28]. Besides, some studies have surveyed subjective aspects in classrooms. This is of primary importance indeed: it may happen that a classroom that meets daylight criteria is negatively judged by the occupants and vice versa. The review from Wu et al. [29] highlighted the need to examine the relationships between the responses of school occupants and the quantity of daylighting. From this viewpoint, Castilla et al. [30] used the Semantic Differential method to analyze students' responses in university classroom in their own words, showing that students' affective structure comprises six independent factors: functionality and layout, cosy and pleasant, concentration and comfort, modern design, daylight and outward facing, and artificial lighting. However, previous studies that assessed subjective responses showed contrasting results regarding the relationship between subjective and objective evaluation of the indoor lighting environment. Some studies reported no or small associations between perceived indoor lighting quality and objective parameters: for instance, on the one hand, Baloch et al. [31] found no discernible association between the parent's or children's perception of illumination, direct sunshine on benches, type of lighting, and openable windows in 53 schools across Europe. On the other hand, Liu et al. [32] reported a significant impact of classroom lighting on visual perception (i.e., skin preference, multi-dimensional lighting atmosphere evaluation), but no relationships between lighting and the comfort for reading, attention, and alertness expressed by the participants. Other studies showed high correlations between perceived visual comfort and measured lighting indicators: for instance, Ricciardi and Buratti [33] correlated subjective judgments expressed by university students and objective measurements of physical quantities related to thermal, acoustical, and lighting comfort. Even though daylighting represented a small share of the investigation (two questions of the survey), a good correlation was observed between workplane illuminance and subjective judgments on daylight adequacy. Similarly, De Giuli et al. [34] investigated how indoor environmental quality conditions in primary schools were perceived by pupils, asking them to express their satisfaction about the environment, the school, and the interaction with the building, and their reaction when discomfort occurred. The results showed that children passively accept indoor conditions, as classroom conditions depend mainly on teachers' preferences. Finally, Zomorodian et al. [35] correlated subjective perceptions expressed by students in four LEED certified educational buildings to climate-based daylight metrics, showing robust correlations.

Within this frame, this study presents findings from an investigation on daylighting in five Italian universities, as part of the DAYKE-Italy project, a spin-off study of project "Daylighting Knowledge in Europe (DAYKE)". DAYKE is a research project aimed at assessing the degree of daylight knowledge and teaching in Europe among designers and within design schools. The survey, which is still ongoing, has so far collected data from eleven European architecture schools in France, Germany, Italy, the Netherlands, Poland, Spain and Switzerland [36-39].

In this paper, the methodology of the DAYKE survey (henceforth DAYKE-Europe) was replicated in five Italian universities, as part of the DAYKE-Italy spin-off. Besides, dynamic simulations were also performed to calculate a broad set of metrics (daylight, circadian and energy-related), in order to correlate subjective judgments and objective metrics.

1.1 Aims and objectives

The following objectives were set for the study:

(i) to investigate the correlation that exists between daylight metrics and subjective responses expressed by students:

RQ1: do daylight metrics prescribed in different standards/protocols fit the subjective responses expressed by students? This RQ is in line with the investigation carried out by Zomorodian et al. [35]

RQ2: can a classroom noncompliant with daylight metrics/criteria be positively judged by students, and vice versa?

(ii) to investigate the correlation that exists between circadian metrics (namely: the equivalent melanopic illuminance EML) and subjective responses expressed by students:

RQ3: do circadian metrics based on the EML (equivalent melanopic lux) fit the subjective responses expressed by *students?*

(iii) to investigate the potential energy savings due to harvesting of daylighting available in the classrooms and to what extent this can be correlated to some objective metrics:

RQ4: is there a correlation between energy use/saving and some daylight metric/criterion?

The next sections are subdivided as follows: an overview of objective metrics (daylight, circadian, and energy-related) is addressed in Section 2. Section 3 describes the method of the study: this relies on a combination of a survey to collect subjective responses on daylight perception in eight Italian university classrooms and simulations of the same spaces to determine the objective metrics. Objective metrics and subjective scores are then correlated through statistical analysis techniques. The results are presented and discussed in Section 4. Finally, Section 5 draws the conclusions of the study.

2. Overview of existing objective metrics minimum performance criteria for daylighting

2.1 Daylight metrics

Several metrics exist in the literature to quantify the daylight provision in a room:

- *average daylight factor DF_m.* In the Italian context, the regulation body still refers to the DF_m concept [40-43]. It is well known that DF_m does not account for crucial factors such as climate, latitude, orientation, and use of moveable shades to control the sun penetration. Nonetheless, it is still the reference metric in many European countries, mostly due to its simplicity. Besides DF_m, an earlier Italian version of LEED protocol [44] introduced a requirement in terms of a minimum area (75%) of the occupied spaces that must show a point daylight factor DF_P over 3%. This metric is hereby referred to as 'spatial daylight factor sDF'. Based on the current formulae, the DF concept linearly increases as the daylighting admitted into the room increases
- *Climate-Bases daylight modeling CBDM.* Unlike the DF concept. This approach considers the annual variation of climate conditions for the site under analysis, latitude, room orientation, workplane illuminance, presence and control of moveable shades [45]. A new set of 'dynamic' daylight metrics have been defined, such as the Annual Light Exposure ALE [46-47], the Daylight Autonomy DA [48], the spatial Daylight Autonomy $sDA_{300,50\%}$ and the Annual Sunlight Exposure $ASE_{250,1000}$ [49], the Useful Daylight Illuminance UDI [50], and the Daylight Glare Probability DGP [51]. Besides DGP, also the vertical illuminance at eye-level is used as a proxy for glare analyses [52]. It is worth stressing that above metrics, except ALE, are defined based on 'thresholds', as they represent the percent of occupied annual time when illuminance lies in a certain range. Instead, ALE does not have thresholds nor ranges, but it represents the daylight amount in a space in absolute terms. An overview on climate-based daylight metrics and relative simulation tools can be found in [53-55]. CBDM-based metrics have gained a large consensus among

daylighting researchers and some of them have been introduced in protocols and recommendations for sustainable architecture [56-57]. Within this frame, the recent European Standard EN 17037:2018 on 'Daylight in buildings' [58] introduced a new approach, based on a 'climate-based' DF_m: a specific minimum $DF_{m,target}$ is recommended based on the site (through the median external diffuse unobstructed illuminance $E_{v,d,median}$, expectedly higher for lower latitudes and lower for higher latitudes), and on the workplane illuminance. As a further constraint, the standard requires that the DF_m performance be guaranteed in at least 50% of the regularly occupied space. Besides, the EN 17037 also contains DGP-threshold values for annual glare verifications.

2.2 Circadian metrics: EML

The spectral distribution of daylight plays a key role on the stimulation of the circadian system and therefore on 'human factors', for instance in terms of reduced sleepiness and increased vitality, alertness, productivity, and cognitive performance and satisfaction for the occupants ('non visual' effects of light) [10; 59-65]. New dedicated metrics were introduced, such as the Circadian Stimulus CS, the Circadian Action Factor CAF and the Equivalent Melanopic Lux EML [14; 65]. In this study, it was decided to use EML: this measures the biological effects of light on humans, based on the five photosensitive retinal ganglion cells (ipRGCs) that regulate the human circadian response to light. EML translates how much the spectrum of a light source stimulates ipRGCs and affects the circadian system [66-67]. It is measured vertically at observers' eyes. Along with EML, the melanopic ratio R was defined to connect the photometric illuminance and EML (EML = E*R) and thus to quantify the circadian content per each lx of the photometric illuminance. EML was included in the WELL protocol [68], or in reports from the Collaborative for High Performance Schools (CHPS) [69]. The EML value increases as daylighting increases, without thresholds. The EML value increases as daylighting increases, without thresholds. Recently, CIE (Commission Internationale de l'Eclairage) has evolved the EML concept into the melanopic equivalent daylight illuminance EDI, by replacing the original equal-energy spectrum with a daylight spectrum (illuminance D65) as reference [70]. The two metrics are linked through a simple correction factor: EDI = EML * 0.9058. The original EML was used for the purpose of the study.

2.3 Energy-related metrics

In Europe, the energy demand for lighting is ruled by the European standard 15193-1:2017 [71], which introduced the LENI index (Lighting Energy Numeric Indicator) to quantify the annual energy performance for lighting of a building. LENI accounts for the power of the lighting systems (including the parasitic power of control systems and emergency lamps), type of control system, daylight supply indoors, workplane illuminance, and occupancy profile. The standard also provides a short list of informative benchmark values [72]. However, a limiting value of 19 kWh/(m^2yr) was used in this study [73], as such limit is based on an occupancy profile consistent with the one adopted for simulations.

Table 1 summarizes the various metrics (daylight, circadian, and energy-related) considered in the study.

Table 1.
Daylight, circadian, and energy metrics used in the study, along with the target values according to legislation, standards, or protocols.

Metric	Unit	Definition	Target value
Daylight metrics			
DF_m	[%]	Ratio of the internal average illuminance on an interior surface to the external horizontal unobstructed diffuse illuminance due to skylight only (overcast sky)	$DF_m \geq 3\%$ [40] $DF_m \geq 2\%$ [42]
$DF_{m,climate\ based}$	[%]	Ratio of the internal average illuminance on an interior surface to the median external horizontal unobstructed diffuse illuminance due to skylight only (measured annually at the considered site)	$DF_m \geq 1.8\%$ for Turin-Venice [58] $DF_m \geq 1.6\%$ for Naples [58] $DF_m \geq 1.8\%$ for Palermo-Catania [58]
sDF	[%]	Percent of regularly occupied space where DF > 2% (DF > 3% for classrooms) is detected	sDF ≥ 2% for workspaces [44] sDF ≥ 2% for classrooms [44]
DA [%]	[%]	percent of the occupied time during a year when a minimum illuminance threshold is met by daylight alone	
cDA [%]	[%]	Same definition as for DA, but partial credit is attributed to time steps when the daylight illuminance lies below the minimum illuminance level	
$sDA_{300,50\%}$	[%]	percent of an analyzed area that meets a minimum daylight illuminance level of 300 lx for 50% of the operating hours per year (3650 h/year)	$sDA_{300,50\%} \geq 40\%$ - sufficient [56] $sDA_{300,50\%} \geq 55\%$ - preferable [56] $sDA_{300,50\%} \geq 75\%$ - optimal [56]
$ASE_{1000,250}$	[%]	percent of an analyzed area that exceeds a specified direct sunlight illuminance level of 1000 lx for more than 250 hours of the operating hours per year (3650 h/year)	$ASE_{1000,250} \leq 10\%$ (*otherwise, identify how glare is addressed*) [56]
ALE	[lx h]	cumulative amount of daylight incident on a point of interest over the course of a year (daylight dose)	
$UDI_{100\text{-}3000}$	[lx h]	Percent of the occupied times of the year when illuminances across the workplane lie within a range considered "useful" by occupants – 100 to 3000 lux	$UDI_{100\text{-}3000} \geq 80\%$ [57]
$F_{DGP,exceeded}$	[%]	Percent of occupied time during the course of a year when DGP values are over 0.40 (disturbing glare)	$F_{DGP>0.40} < 5\%$ [58]
$E_{v,eye>1600}$	[%]	percentage of the occupied time during the course of a year when a minimum vertical illuminance threshold at occupant eye-level is met by daylight alone	$E_{v,eye} \geq 1600$ lx [74]
Circadian metric			
EML	[lx]	Measure, weighted to the ipRGCs response to light, of how much the spectrum of a light source stimulates ipRGCs and affects the circadian system	EML ≥ 120 lx [68] EML ≥ 250 lx [68]
Energy metric			
LENI	[kWh/ (m^2yr)]	Annual net energy demand for electric lighting needed to meet workplane illuminance requirements in each building zone	No applicable benchmark in [71] LENI < 19 kWh/(m^2yr) [72]

3. Method

The investigation method used in the study was based on a combination of two approaches:

(i). a survey, to collect subjective judgments from a large sample of students; the survey was the one developed within DAYKE-Europe [36] and was distributed in eight Italian classrooms within the DAYKE-Italy project

(ii). simulations, to calculate a large set of objective metrics: daylight, circadian, and energy-related. These metrics are the ones specifically required in technical legislation and standards on daylighting and well-being, or in energy-environmental protocols.

Subjective responses from the survey and objective metrics from simulations were statistically correlated to investigate if objective metrics can be reliable indicators to describe the student perception of a daylit classroom.

3.1 DAYKE-Italy: a survey to collect subjective judgments on daylighting from students

The DAYKE-Italy project is a spin-off of DAYKE-Europe. Results from DAYKE-Europe were presented in previous publications [36-38].

The DAYKE project consists of three primary areas of investigation, carried through an ad-hoc survey: (i) *perception* of a daylit space (university classrooms in schools of architecture), in terms of visual performance and comfort perceived by the occupants; (ii) *preferences* about daylighting; and (iii) *knowledge* about daylighting, in terms of daylighting metrics, standards/regulations, and simulation tools for daylighting.

The DAYKE-Europe project was replicated into DAYKE-Italy with the aim of creating an Italian network on 'daylighting education' to collect and share subjective assessment about daylighting, to increase the awareness about daylighting issues and to implement a common strategy into university curricula in Italian universities, where the architects of the future are educated.

The results obtained on the '*knowledge*' section have been the object of a dedicated paper [39].

In this paper, results from DAYKE-Italy about the '*perception*' section are presented and correlated to objective metrics (daylight, circadian, and energy), determined through numerical simulations. The DAYKE questionnaire was administered to Bachelor and Master Science students in eight classrooms in five universities across the Italian territory (Turin and Venice in northern Italy, Naples in central Italy, and Catania and Palermo in southern Italy, see Fig. 1). The classrooms were selected to have a sample able to represent several different scenarios in terms of daylight quantity and distribution across the room, due to different climate and architectural features (orientation, window area, room depth). Students who participated in the survey were different for each classroom considered, thus each student filled in the questionnaire only once.

The survey was administered through two campaigns: spring 2019 session (eight classrooms) and fall-winter 2019-2020 session (five classrooms of the eight used in spring session).

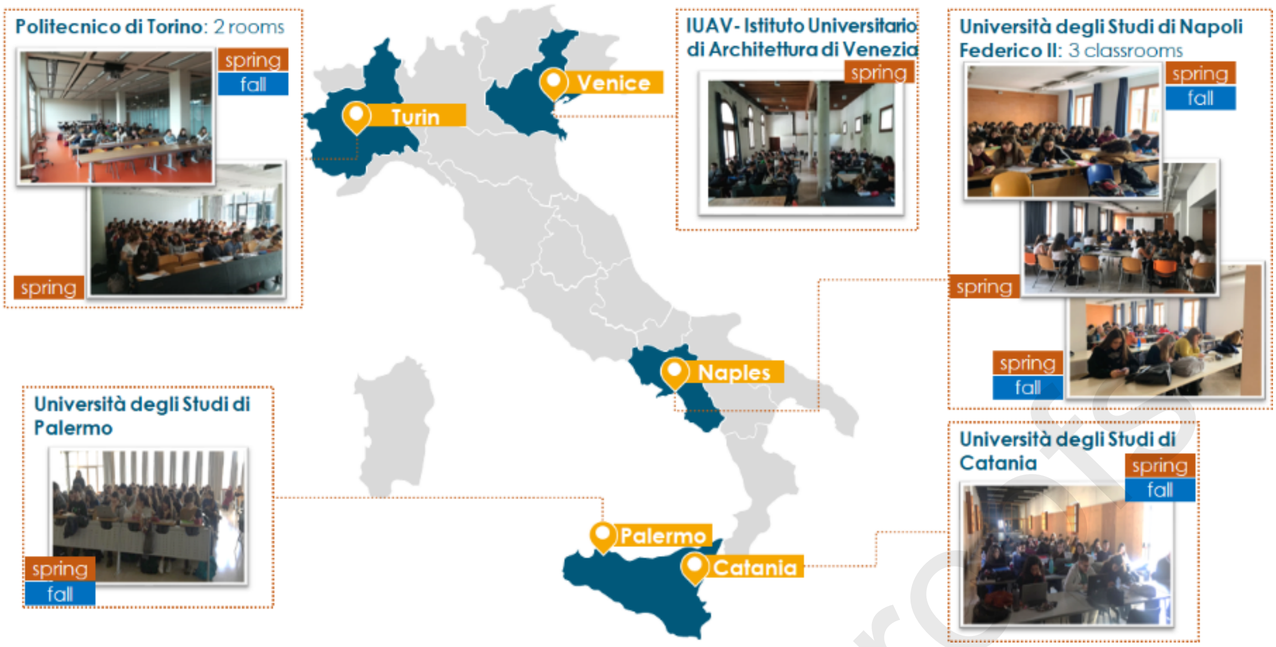


Fig. 1. Synthetic visualization of the eight classrooms used in the DAYKE-Italy study.

Synthetic information about the eight classrooms used for the study is provided below:

1. TUR-1: this classroom is in the Lingotto campus, a requalification of the historical building built for former FCA automobile car manufacturing (FIAT). The requalification project was designed by Renzo Piano in 2003 and included the transformation of a wing of the building into a university campus. The classroom has large windows (window-to-floor ratio WFR = 0.27; window-to-wall ratio WWR = 0.70) facing North, North-East, with two independent moveable shades operated by the occupants. Windows are unobstructed and with the glazing aligned with outside face of the façade (vertical sky component VSC = 0.5).
2. TUR-2: this classroom is in the new campus achieved by Politecnico di Torino in the decade 2000-2010. It has an entirely glazed South-East-facing façade (WFR = 0.27; WWR = 1), with moveable fiber shades operated by the occupants. The windows face a courtyard with grass and other classrooms all around.
3. VEN: this classroom is in the former Convent of Santa Teresa, built in the second half of the 17th century as a building complex that develops around a large cloister with arched porticos. The convent was restored by 'Università IUAV di Venezia' in late 1990s - early 2000, with architectural renovation and transformation operations necessary to host the new teaching and research activities. The classroom (formerly a storage hall) is on the ground floor, with two series of windows on two opposite walls, one series facing the cloister with a portico, the other facing a garden with distant buildings. All windows present independent moveable shades (internal curtains), operated by the occupants. Internal and external surfaces of walls are painted in white color.
4. NAP-1: this classroom is located on the second of a six-story articulated building, facing one of its two large internal courtyards. The building was created by merging three previous buildings: a Church, started in 1564, a conservatory

for poor girls and a bank, administered by the Confraternity of the Holy Spirit. During the '60 of the 20th Century, it was restored and partially redesigned by Marcello Canino. After this renovation, the building hosted offices and a bank. During the last part of the 20th Century, it was acquired by the Faculty of Architecture of the University of Naples Federico II and refurbished to comply with the new function. To-date, it hosts the almost totality of classrooms and teachers' offices of the Department of Architecture.

It has West-facing windows with WFR = 0.14 and WWR =0.28, with movable opaque curtains, generally kept open. Façades of the internal courtyard, with yellow plaster finish, represent most of the outside view, being the sky view limited to the locations very close to the windows (VSC = 0.20).

5. NAP-2: this classroom is located in the same building as classroom NAP-1, but on the fifth floor. It is smaller than NAP-1, but with similar ratios: WFR= 0.15 and WWR = 0.26. However, the South-oriented windows that face the internal courtyard allow the direct sky view from many desks (VSC = 0.36).
6. NAP-3: this classroom is located in the same building as classroom NAP-1 and NAP-2, but on the fourth floor. It also faces the internal courtyard, with windows oriented North, with WFR = 0.15 and WWR = 0.22. The external view toward the courtyard is very similar to NAP-2, with a little reduction of the sky view (VSC = 0.31).
7. PAL: this classroom is located on the third floor of the building that hosts the Department of Architecture University Campus of Palermo. Built around 1990, it includes a central, four-storey building (the lower two below street level and the upper two above) and a C-shaped building around the main one, below the street level. The classroom has two clerestory windows in two adjacent walls, one facing northeast (partially obstructed by another wing of the building itself) and one facing northwest, unobstructed. Both windows are equipped with independent moveable opaque curtains, which can be operated by the occupants.
8. CAT: this classroom is in an ancient fortress (known as 'Gaetano Abela' barracks) built in 1735 on Ortigia island, close to the sea. Since 2005, it has hosted the Special Teaching Facility for Architecture of the University of Catania. It is a rectangular building with a large internal courtyard, originally intended for military training of the soldiers based in the nearby Maniace Castle. The building's original designation as a military barrack led to the use of a compact building shape, not permeable with the outside. The windows on the external façades, in fact, are quite small (1.7 m^2), while the windows that face the courtyard are larger (almost 2.2 m^2). At a glance, the window area appears to be small to comply with the daylighting requirements for educational activities.

Table 2 summarizes the main features of the classrooms used in DAYKE-Italy, while Annex 1 reports more detailed iconographic information.

Table 2.
Features of the eight classrooms used for the study. Incompliant values with respect to Italian building regulations are highlighted in red bold.

Classroom code	LAT. [°]	Window orientation	Sizes (WxDxH) [m]	Floor area [m²]	WFR [-]	WWR [-]	VSC [-]	LPD [W/m²]
TUR-1	45.1°	NE	19 x 8.5 x 3.9	160.8	0.27	0.70	0.50	8.1
TUR-2	45.1°	SE	14.3x11.2x3.2	160.5	0.29	1.00	0.38	10.8
VEN	45.4°	SE (side 1) NW (side 2)	19.7x8.9x4.7	174.4	0.18	0.17(*)	0.12(*)	6.3
NAP-1	40.9°	W	14.9x6.7x3.3	100	0.14	0.28	0.20	4.3
NAP-2	40.9°	E	12.4x5.7x3.3	70.6	0.15	0.26	0.36	6.1
NAP-3	40.9°	N	17.8x6.5x3.3	109.7	0.15	0.22	0.31	9.2
PAL	38.1°	NW (side 1) NE (side 2)	21.3x14.1x3.15	964.1	0.14	0.72(*)	0.41(*)	5.3
CAT	37.5°	N (side 1) S (side 2)	34.1x6.6x4.9	222.4	**0.08**	0.06(*)	0.45(*)	7.1

As shown in Table 2, three objective metrics concerned with the daylight provision in the eight classrooms were considered: WFR (window-to-floor ratio, i.e. window area to the floor area ratio), WWR (window-to-wall ratio WWR, i.e. ratio of the window area to the wall area that contains the windows), and VSC (vertical sky component VSC, which quantifies the amount of sky 'seen' by a windows). For a better clarity, the three metrics are visualized in Figure 2. For the classrooms that have windows in two different walls (VEN, PAL, and CAT), WWR and VSC were calculated independently for each façade and then averaged (through a window area weighted average). WFR and WWR account for the window area, while VSC quantifies the role played by the external urban setting in terms of obstruction. It is worth stressing that a minimum WFR value of 0.125 (WFR > 0.125) is prescribed by Italian building regulations as a ventilation requirement to guarantee a suitable air exchange in the room. However, it is commonly used by building practitioners and professional designers as a daylighting criterion as well, due to its simplicity and ease-of-use [43].

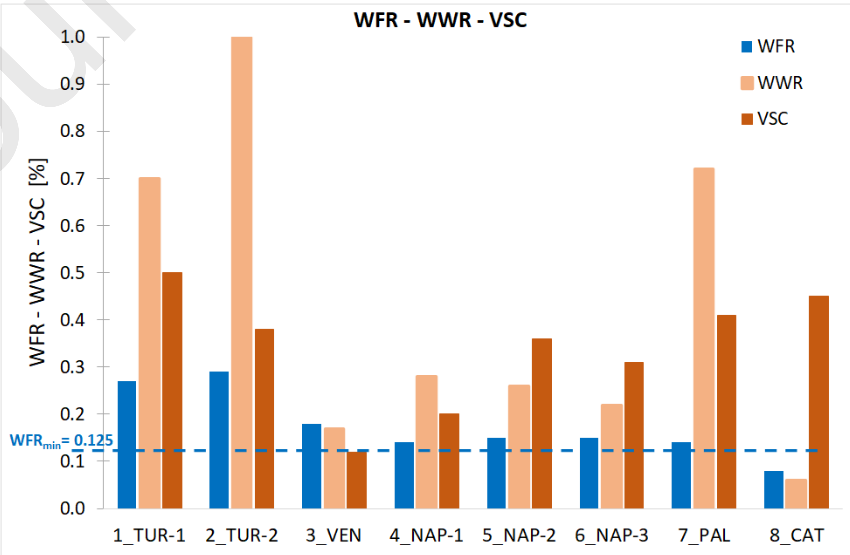


Fig. 2. WFR, WWR, and VSC values for the eight classrooms used in the DAYKE-Italy study.

As shown in Fig. 2, the following aspects stand out:

- there is one case of non-compliance with the minimum WFR requirement, which is the classroom located in Catania, for which WFR = 0.08. This is related to the transformation of a former fortress into an educational building, which has quite different priorities (defence in one case, teaching in the other) and daylighting requirements; on the other hand, windows do not have impacting obstructions ahead (VSC = 0.45)
- VEN is the case with the most impacting obstruction (VSF = 0.12), due to its position on the ground floor, with windows on one side facing the cloister porch and on the other side facing quite close buildings
- three classrooms (TUR-1, TUR-2, and PAL) have quite large window areas: the WWR is particularly high for TUR-2 (WWR = 1) and PAR (WWR = 0.72). On the other hand, PAL has a large floor area, which results in a WFR slightly above the minimum standard requirement (WFR = 0.14)
- the three classrooms in Naples have a comparable WWR, but different obstructing settings, because of their position in different floors facing the courtyard
- consequently, a higher daylight provision is expected in TUR-1, TUR-2, and PAL, opposed to a lower daylight provision expected in VEN, CAT, and NAP-1.

3.1.1 DAYKE-Italy questionnaire

The questionnaire used in DAYKE-Italy was the same as previously used in DAYKE-Europe. It was administered in Italian; however, the English version is reported in the paper to ease comprehension for readers.

The questionnaire consists of five sections: (1) environmental impressions; (2) perception; (3) preferences; (4) knowledge and (5) socio-demographic personal information. The present paper presents subjective responses from sections (1), (2), and (5).

Different types of scales (unipolar and bipolar) were used in the different sections of the survey: Table 3 shows in detail the questions used in the survey for Sections 1, 2, and 5.

Table 3.
Online Survey: questions of sections 1 (Environmental impression), 2 (Preferences), and 5 (General Information)

Section	Question		Scale proposed for the answer
1. Environmental impression			
1.1 Location	1.1.1	What is the weather like now? (*)	Snowing – Raining – Cloudy – Partly cloudy – Sunny
	1.1.2	For your comfort related to daylighting (visibility and heat), how do you describe such weather	Very unpleasant – Unpleasant – Neutral – Pleasant - Very pleasant
	1.1.3	What is your position in relation to the window/s?	Far Away – Far - Neither Near, Nor Far – Close - Very Close
	1.1.4	What is your position in relation to the (black)board?	Far Away – Far - Neither Near, Nor Far – Close - Very Close
	1.1.5	Can you see the sky from your sitting position?	Absolutely not - Yes, but only a small portion - Yes, a large portion

	1.1.6	Please describe your current mood	Very negative – Negative – Neutral – Positive - Very Positive
2. Perception			
2.1 Overall daylight environment	2.1.1	The quantity of daylight is:	1: Too low – 2: Low – 3: Acceptable – 4: High – 5: Too high
	2.1.2	The daylight through the glazed areas is:	1: Too low – 2: Low – 3: Acceptable – 4: High – 5: Too high
	2.1.3	The number of windows for this room is:	1: Too low – 2: Low – 3: Acceptable – 4: High – 5: Too high
2.2 Windows and View out	2.2.1	Dark zones are	1: Absent – 2: Very low - 3: Low– 4: High – 5: Very high
	2.2.2	Obstructions out of the windows are	1: Absent – 2: Very low - 3: Low– 4: High – 5: Very high (reverse coded)
	2.2.3	Distractions due to the view out are	1: Very poor – 2: Poor - 3: Acceptable– 4: High – 5: Very high
	2.2.4	The pleasantness of the view out is	1: Absent – 2: Very low - 3: Low– 4: Good – 5: Very good
2.3 Windows and shading	2.3.1	Daylight control by shading system is	1: Very poor – 2: Poor - 3: Acceptable– 4: Good – 5: Very good
	2.3.2	The maintenance of the shading system is	1: Very poor – 2: Poor - 3: Acceptable– 4: Good – 5: Very good
	2.3.3	The cleanliness of glazing is	1: Very poor – 2: Poor - 3: Acceptable– 4: Good – 5: Very good
2.4 Qualitative aspects	2.4.1	The pleasantness of the overall daylight is	1: Very poor – 2: Poor - 3: Acceptable– 4: Good – 5: Very good
	2.4.2	The contribution of daylight to create a stimulating environment is	1: Very poor – 2: Poor - 3: Acceptable– 4: Good – 5: Very good
	2.4.3	Your concentration due to the overall daylight is	1: Very poor – 2: Poor - 3: Acceptable– 4: Good – 5: Very good
	2.4.4	The overall comfort due to daylight is	1: Very poor – 2: Poor - 3: Acceptable– 4: Good – 5: Very good
	2.4.5	How comfortable do you feel the lighting of the room for reading the text in your device	1: Very poor – 2: Poor - 3: Acceptable– 4: Good – 5: Very good
	2.4.6	How comfortable do you feel the lighting of the room for reading and writing at your desk	1: Very poor – 2: Poor - 3: Acceptable– 4: Good – 5: Very good
	2.4.7	How comfortable do you feel the lighting of the room for reading on (black)board	1: Very poor – 2: Poor - 3: Acceptable– 4: Good – 5: Very good
5. Personal information			
5.1 About you	5.1.1	What is your gender?	Male – Female
	5.1.2	What is your age?	*Open answer*
	5.1.3	What is your nationality?	*Open answer*
5.2 About your education	5.2.1	Please indicate your University	*Open answer*
	5.2.2	Please indicate your Faculty	*Open answer*
	5.2.3	Which academic degree are you taking?	1st Cycle (Bachelor's Degree or similar) - 2nd Cycle (Master Degree or similar) - MA/MSc or PhD – other (specify)
	5.2.4	Please provide the start date and the year (1st, 2nd, 3rd, 4th, 5th) of the course?	*Open answer*
	5.2.5	What is your field of study?	Architecture - Urban design - Lighting design – other (specify)
	5.2.6	Have any of the classes you have attended during your studies addressed daylighting analysis and/or calculations?	Yes – No (if yes: which ones?)
	5.2.7	Have you ever received extra-curricular lectures on daylighting subjects?	Yes – No (if yes: which ones?)

(*) the students self-reported the weather conditions as they were able to perceive based on daylighting in the classroom when filling the questionnaire. Weather conditions were double-checked by the research team to identify potential inconsistencies.

3.2 Simulations

Two simulation tools were used to calculate the huge dataset of metrics (daylight, circadian, and energy-related) described in Section 2 and to be used for correlation with the subjective responses from the students. They both are add-on for Rhino: DIVA-for-Rhino and ALFA. The eight classrooms used in the study were geometrically modeled in Rhino to launch DIVA [75] and ALFA [76] simulations.

3.2.1 Simulations of daylight and energy metrics: DIVA-for-Rhino

DIVA-for-Rhino was used to calculate both static (DF_m and sDF) and climate-based daylight metrics (DA, cDA, $sDA_{300,50\%}$, $ASE_{1000,250}$, ALE, $UDI_{100\text{-}3000}$, DGP, and $E_{v>1600}$). The visible reflectance values of the surfaces were measured in each classroom by using an illuminance-meter (Spectis 1.0 Touch, manufactured by GL-Optics, error: ±4%), measuring illuminance facing the surface and then facing away from the surface, and then calculating the reflectance as a ratio of the two illuminances measured. The approach based on illuminance-meter measures implies that all the surfaces are Lambertian: this assumption is realistic in Italian classrooms, where diffuse materials are installed and specular materials avoided, as recommended by Italian regulations. An error can be committed through this procedure to measure the light reflectance, but the goal of the paper was not to have a 100% realistic model to run simulations for some certification or rating process, but to have a consistent model to have simulations result to be correlated with subjective answers provided by the students. In this regard, it was important to have on the one hand several classrooms where to calculate (through simulations) a huge dataset of metrics, and on the other hand a large dataset of subjective scores, to then sustain robust statistical analyses.

Differently, the visible transmittance value of glazing was found in technical datasheets provided by the technical offices of the universities involved. The visible transmittance was not measured through the procedure based on the illuminance-meter as in this case the error would have been higher, considering that glazings are specular, not diffusing materials.

Three different grids of sensor points were defined for DIVA simulations:

- a horizontal grid (for the calculation of horizontal illuminances) to cover the whole room, 0.8 m above the floor
- a horizontal grid to cover the desk area only (0.8 m above the floor), for the calculation of horizontal workplane illuminances. This was done to calculate objective metrics across the same area where the students were when they filled the survey
- a grid of vertical sensors, in correspondence of the positions occupied by each student, 1.2 m above the floor, facing

the blackboard, to calculate the vertical illuminance at eye-level.

Fig. 3 shows the eight classrooms with the grids over the desk areas. In some cases, the difference between the two horizontal grids (entire area vs. desk area) is quite huge: this is particularly evident for NAP-2, a classroom whose shape and characteristics (presence of large pillars) split the space into two areas and only one of them is actually used during lectures (the other one remains a large circulation area with desk facing a wall used by the students for individual work).

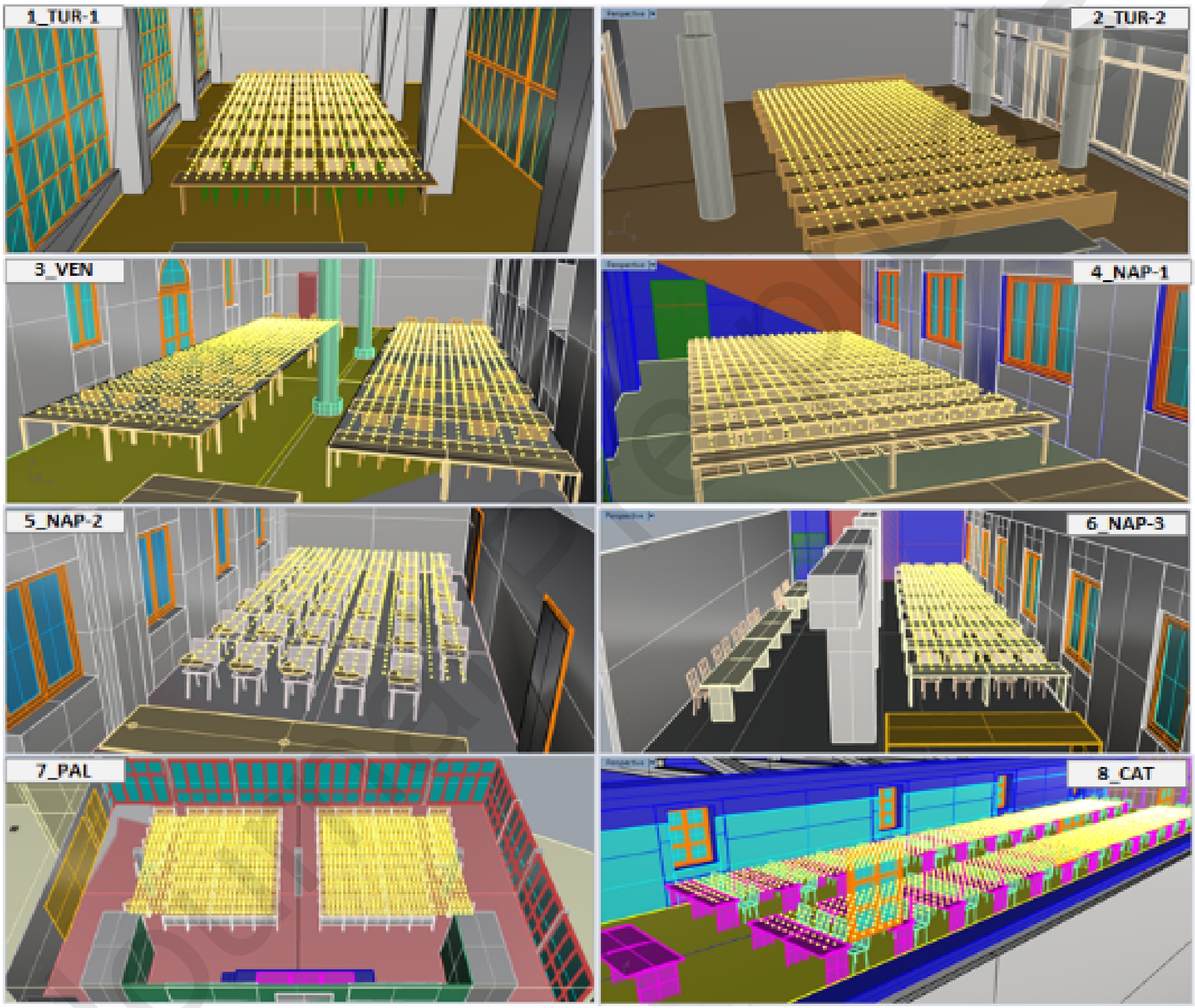


Fig. 3. Grid over the desk area, that is the continuously occupied area in each classroom.

Annual analyses were run to calculate the various daylight metrics, using the climate files of the five locations, all available on the Energy Plus website. According to the definition of each metric, the values calculated at each sensor point of the grid considered were elaborated as follows:

- calculation of the average value of the metric across the grid: this is the case of DF_m, DA, cDA, and $UDI_{100,3000}$
- calculation of the fraction of grid points where the considered metric was compliant with the reference threshold: this is the case of sDF, $sDA_{300,50\%}$, $ASE_{1000,250}$.

The following simulation parameters were set for Radiance, used by DIVA: ab 6, ad 1000, as 20, ar 300, aa 0.05. A different parameter set was used for the calculation of $ASE_{1000,250}$, namely ab = 0. New specific materials were built and added to the Radiance library available in DIVA, to accurately reproduce the visible reflectance that was measured in-situ. Plastic materials were used for the purpose, as the materials were assumed to be Lambertian.

Consistently with the definitions of $sDA_{300,50\%}$ and $ASE_{1000,250}$ [49], an annual occupancy profile 8 through 18, every day, was assumed, resulting in 3650 h/year. It is not perfectly consistent with the real use of the classroom analyzed, but it was decided to exactly match the assumptions set for the calculation of sDA and ASE. This is a generalization: clearly, each university may have a different actual occupancy profile, and the same applies for every single classroom within the same university, whose use could change over time, from an academic year to the next (this might happen from the Spring to the Winter session). A longer occupancy profile would result in higher LENI values, due to the longer period without daylight, and vice versa. Using the same occupancy profile for all the classrooms allows direct comparison to be done, consistently with one of the goals of the study.

Moveable blinds, operated by the occupants, were modeled. Blinds were pulled down when $E \geq 3000$ lx was detected at any time-step of the annual simulation at any sensor point and were then retracted when $E < 300$ lx was detected. Accordingly, the blind utilization profile was also recorded as output ('closed_blind', as '*percent of the annual occupied time when the blind is closed*'). This metric was also correlated with the subjective responses from students.

As far as lighting energy simulations are concerned, the annual energy demand for lighting (LENI) was calculated for two controls: (i) a manual control, which is the control type installed in the eight classrooms of the study ($LENI_{MAN}$); and (ii) a daylight responsive photo-dimming sensor, which responsively dims the light output from luminaires when illuminance drops below 300 lx and switches lights off when it is calculated to be over 300 lx ($LENI_{DR}$). The potential energy saving was therefore calculated through the formula:

$$\text{saving} = \Delta LENI = (LENI_{DR} - LENI_{MAN})/LENI_{MAN} * 100 \quad [\%] \qquad (1)$$

A validation of the models of the eight classrooms was not carried out, for two main reasons: (i) it is usually quite difficult to calibrate a highly accurate model for daylight simulations, as it would be necessary to refer to a 'perfect' overcast sky (as close as possible to the CIE overcast sky) to measure daylight factor values in the real space and to compare them to simulated values. Moreover, this procedure should have been repeated for all the eight classrooms; (ii) the goal of the study was not to have a 100% realistic model to run simulations to get, for instance, an energy certification label or to get credits from some protocols or rating systems (such as LEED); instead, the goals was to compare daylight, circadian, and energy quantities (that describe daylighting in a space) with the perception of that daylighting as expressed by individuals. For this purpose, the aim was to build 3d models as close as possible to the real environments, by measuring visible reflectance values or using visible transmittance values provided by manufactures, and by accurately reproducing the geometry of each room and of the obstructing contexts.

3.2.2 Simulations of circadian metrics: ALFA (for-Rhino)

ALFA was used to calculate the circadian metric EML. The software also provides as output the melanopic ratio R and the vertical illuminance at eye-level ($E_{v,eye}$). As the goal of the study was to correlate objective metrics and student subjective responses, the sensor points were positioned 1.2 m above the floor, facing forward (towards the teacher's desk and the blackboards/projection screens). No other direction of observation was taken into consideration. The ALFA-models were built trying to match the DIVA-model as closely as possible: for this purpose, materials with the same visible reflectance as the ones measured in each real classroom and used in DIVA were selected from the ALFA library, also paying attention to select a material with a similar color, to account for its spectral reflectance.

Unlike daylight metrics, which were calculated for 3650 occupation hours per year, circadian metrics were calculated only for the specific time-steps when the survey was filled (point-in-time analyses), during both the spring and the fall/winter session. This was done to explore a more direct correlation with the subjective responses from students. For each reference day, simulations were repeated under both a clear and an overcast sky to analyze the range of EML levels for comparative purposes; however, the specific sky condition found at the time of the survey was used for the correlation with the subjective judgments.

3.3 Statistical analyses

Descriptive statistics were computed for the variables of interest. Then, in order to identify the main factors that express different perceived aspects of daylighting and to eliminate not reliable items, a series of Exploratory Factor Analyses (EFA) with an Oblimin rotation was performed on the scores obtained for the 23 items listed in Table 3. Some items were eliminated, based on either one of two criteria: items loading < 0.40 on all factors, and items with factor loadings $\geqslant 0.40$ on more than one factor. Cronbach's Alphas were also computed to measure the reliability of the extracted factors. Factors scores were then computed as the sum of the individual items for each factor. The simulation results and subjective measurements underwent a Kolmogorov-Smirnov test to control for any possible deviations from a normal distribution. Because the test showed that many variables could not be considered normally distributed, the relationships between daylight and circadian metrics and the responses expressed by students were investigated by computing a series of Spearman's rank correlation coefficients (ρ). The SPSS (Statistical Package for Social Science) software v. 26 [77] was used for statistical analyses.

4. Results and discussion

4.1 Subjective results and statistical analyses

4.1.1 Description of the sample

Five hundred and forty-two students (60% females and 40% males) filled in the questionnaire. The respondents were distributed as follows: 31.9% from Naples, 24.6% from Palermo, 23.9% from Turin, 13.0% from Catania, 6.6% from Venice. Overall, the participants had a mean age of 22.2 years (SD=3.4) and 53.4 % of them were attending the Bachelor of Science curriculum (46.6% Master of Science).

4.1.2 Factor analysis

The factor analysis computed on the questionnaire items yielded five factors that explained 74.9% of the variance of the data. Table 4 shows the factor loadings and the reliability measures.

The first factor was labeled "*Daylight quantity*" and includes items referring to the overall quantity of daylight in the room and the daylight amount entering the room through windows. The second factor, "*Visual performance*", includes items referring to comfort perceived in accomplishing visual tasks on a desk, device (computer screen, tablet), and (black)board. The third factor was labeled "*Daylight quality*" and it includes daylight-related overall pleasantness and comfort and its ability to create a space that favors concentration and creates a stimulating environment. The fourth factor, "*Window quality*", referred to the maintenance and control of the shading system and the cleanliness of glazing. Finally, the fifth factor, "*View out quality*", deals with items that investigate the presence of obstructions out of the windows and the pleasantness of the view out. It can be noted that factor three, "*Daylight quality*", stands out compared to the other ones as it explains almost 40% of the variation of the data.

Table 4.
Factor loadings and the reliability measures.

Items	Rotated factor loadings				
	Daylight quantity	Visual performance	Daylight quality	Window quality	View out quality
The quantity of daylight is	.874				
The daylight through the glazed areas is	.881				
How comfortable do you feel the lighting of the room for reading the text in your device		.854			
How comfortable do you feel the lighting of the room for reading and writing at your desk		.841			
How comfortable do you feel the lighting of the room for reading on (black)board		.887			
The pleasantness of the overall daylight is			.719		
The contribution of daylight to create a stimulating environment is			.914		
Your concentration due to the overall daylight is			.910		
The overall comfort due to daylight is			.889		

Daylight control by shading system is				.703	
The maintenance of the shading system is				.868	
The cleanliness of glazing is				.791	
Obstructions out of the windows are					.751
The pleasantness of the view out is					.695
Eigenvalue	.925	1.224	5.435	1.748	1.159
% of explained variance	6.604	8.746	38.823	12.488	8.281
α	.789	.843	.895	.712	.456

4.2 Correlation between objective daylight metrics and subjective responses from students

4.2.1 Objective metrics from DIVA simulation

The results obtained through DIVA in terms of daylight metrics are summarized in Figg. 4-5-6. The outcome confirms the expected trends, that is a large range of daylight performance inside the eight classrooms, expected considering the different architectural features of the spaces in terms of access to daylight.

The following main considerations can be drawn from the results concerning the various daylight metrics considered:

- DF_m (Fig. 4a): three classrooms meet the Italian standard requirement $DF_m \geq 3\%$ (TUR-1, TUR-2, and PAL). NAP-3 also shows a consistency if the desk area is considered instead of the whole area: a large difference was observed in this space (DF_m = 1.36% across the whole area; DF_m = 3.01% across the desk area), due to its architectural features, with pillars that split the space into two areas (desk area and a circulation area). If the criterion $DF_m \geq 2\%$ is adopted [40], the situation remains unchanged, since all the other classrooms showed a $DF_m < 2\%$. Considering the criterion set by EN 17037 in terms of 'climate' DF_m, NAP-2 is result compliant (DF_m = 1.70 across desks). This means that a group of three out of eight classrooms do not comply with any DF_m criterion
- sDF (Fig. 4b): two classrooms only would qualify for the LEED-Italy former requirement concerning the distribution of DF values across the space (sDF ≥ 75%), namely TUR-1 and PAL. Considering the less strict requirement set by EN 17037 (sDF ≥ 50%), TUR-2 qualifies. The other five classrooms are not compliant with sDF requirements
- DA (Fig. 4c): no formal requirement is specified for this metric. However, a theoretical threshold DA ≥ 50% can be considered, consistently with the principles of $sDA_{300,50\%}$: in such a case, TUR-1 and NAP-3 (desk area) are compliant, while PAL, which shows a high DF_m and sDF performance, is not (DA_{desk} = 45.6%), due to long periods when blinds are closed to shade the sun ('closed_blind' = 75%). All the other classrooms show lower DA values: the lowest values are observed in VEN (DA_{desk} = 1.7%) and CAT (DA_{desk} = 16%)
- $sDA_{300,50\%}$ (Fig. 4e): two classrooms only qualify for the 3-point LEED credit ($sDA_{300,50\%} \geq 75\%$), that is TUR-1 and NAP-3 (desk area). No further classroom qualifies for the 2-point LEED credit (sDA300,50% ≥ 55%), while one more classroom qualifies for the 1-point LEED credit (sDA300,50% ≥ 40%), that is PAL. The other five classrooms do not qualify: particularly low is the performance in VEN ($sDA_{300,50\%}$ = 0%) and NAP-2 ($sDA_{300,50\%}$ = 3.7%)

- $ASE_{1000,250}$ (Fig. 4g) and 'closed_blind' (Fig. 4h): the three classrooms with the lowest daylight provision qualify for this credit, namely VEN, CAT, and NAP-3 (which has North-facing windows). The other classrooms have $ASE_{1000,250} \geq 10\%$: according to LEED protocol, "*for any regularly occupied space with $ASE_{1000,250}$ greater than 10%, identify how the space is designed to address glare*". Glare is addressed through moveable shades in all the spaces analyzed. The 'closed_blinds' results show that blinds remain closed for long periods in PAL (75% of occupied time), TUR-1 (68%), TUR-2 (56%), and VEN (52%), which limits the view out for the occupants
- $UDI_{100\text{-}3000}$ (Fig. 4f): 3 classrooms qualify for this requirement set by the UK School Building Programme (TUR-1, NAP-3_desk, and PAL). TUR-2 nearly satisfies the criterion ($UDI_{100\text{-}3000} \geq 78.6\%$ for four classrooms out of eight. Interestingly, PAL showed a moderate performance in terms of DA and $sDA_{300,50\%}$ (1-point LEED credit), but an excellent performance in terms of illuminance values remaining in the 'useful' range 100-3000 lx
- ALE (Fig. 5): it shows a trend consistent with DF_m (except for NAP-3). These two metrics quantify the daylight provision in a space in absolute terms, unlike DA, cDA, sDA, and UDI, which use thresholds to describe the daylighting performance
- $E_{v>1600}$ (Fig. 6): The percent of occupied time when $E_{v,eye}$ is quite limited in all the spaces analyzed. A frequency of 9.9% was observed for TUR-1, while it was < 3% for the other spaces. This is due to the view direction of students, towards the blackboards/projection screens, in a way that they do not receive high amounts of daylight at eye-level. For instance, PAL has large windows (WWR = 0.72), but positioned left and behind students. Consequently, a large amount of daylight is admitted into the room (UDI ≥ 87.1%), but only a minor share reaches students' eyes. For the same reason, the glare occurrence calculated in terms of $F_{DGP>0.40}$ is very low: the percent of occupied time when DGP is disturbing (DGP > 0.40) was < 2% for all the spaces, compliant with the requirement set by EN 17037.

Fig. 4. Results from DIVA simulations for all the daylight metrics analyzed in the eight classrooms.

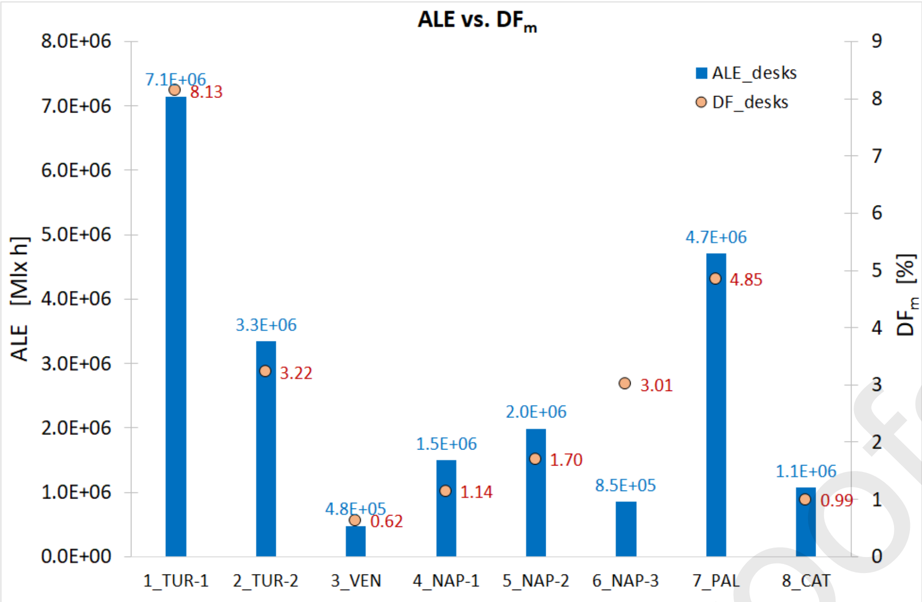


Fig. 5. Results from DIVA simulations for metrics: ALE vs. DF_m.

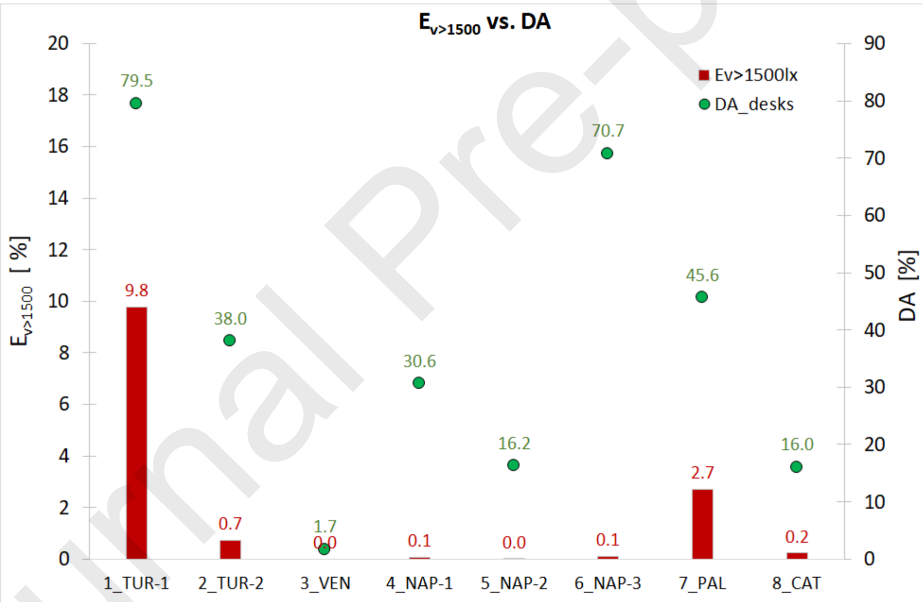


Fig. 6. Results from DIVA simulations for metrics: $E_{v>1600}$ vs. DA.

4.2.2 *RQ1: do daylight metrics prescribed in different standards/protocols fit the subjective responses expressed by students?*

Table 5 reports the Spearman's ρ-correlation coefficients between the objective daylight metrics and the factors extracted from the subjective responses. These correlation coefficients are also graphically visualized in Fig. 7 to allow the reader an easier comparison among the various metrics considered (daylight and geometrical).

Table 5.
Spearmans' ρ-correlation coefficients and significance between daylight metrics and factors extracted from subjective responses.

Daylight metrics	daylight quantity	visual performance	daylight quality	window quality	view out quality
DF_m_desks	0.206***	0.167***	0.255***	0.366***	0.228***
DA_desks	0.194***	0.128**	0.206***	0.283***	0.155**
$sDA_{300,50\%}$_desks	0.199***	0.130**	0.212***	0.279***	0.156**
cDA_desks	0.199***	0.137**	0.214***	0.289***	0.156**
$UDI_{100-3000}$_desks	0.158**	0.104**	0.161***	0.248***	0.124*
BlindsClosed_desks	0.085	0.052***	0.144**	0.149**	0.232
ALE_desks	0.201***	0.174***	0.255***	0.361***	0.237***
VSC	0.337***	0.182***	0.312	-0.011***	0.385***
room_depth	-0.043	-0.019	0.043	0.209***	0.085

*** The correlation coefficient is significant at the p<.001 level
** The correlation coefficient is significant at the p<.01 level
* The correlation coefficient is significant at the p<.05 level.

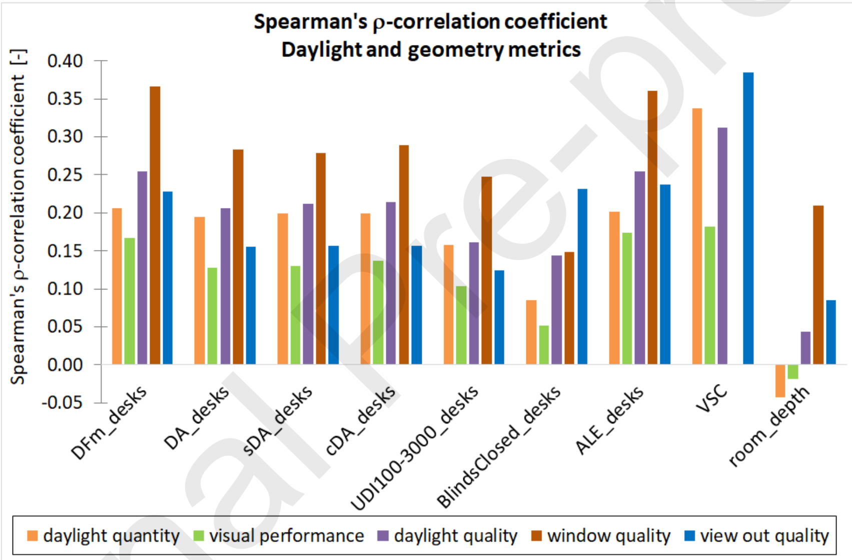


Fig. 7. Spearman's ρ-coefficients for correlation between daylight metrics and subjective judgments for (a) the five factors (1: daylight quantity; 2: visual performance; 3: daylight quality; 4: window quality; 5: view out quality), and (b) two geometric parameters.

The following main considerations can be drawn:

- all the correlations that were obtained have a correlation coefficient lower than 0.40; the lowest correlations were observed for the factor 'window out quality' (except for the metric 'blind_closed').
- the geometric parameter VSC (which quantifies the amount of sky 'seen' by a window) shows the higher correlation for all factors except factor four ('window quality'), for which the correlation is non-significant
- DF_m and ALE show higher correlation with respect to DA, cDA, $sDA_{300,50\%}$, and $UDI_{100-3000}$. Moreover, DF_m and ALE show practically the same correlation, and the same applies to DA, cDA, and sDA300$_{,50\%}$. This is probably due to the fact that DA_m and ALE inherently quantify the daylight provision in a space in absolute terms, while DA, cDA, and sDA are 'metrics with thresholds', which means that they do not quantify the daylight provision in absolute terms, but

rather in relative terms, as they represent the frequency of how often illuminance values lie in a certain range (> 300 lx, or > 300 lx in a given fraction of space); in other words, these metrics show a different sensitivity with regard to the daylight amount in a space. This seems to be confirmed by analyzing ALE (which is a CBDM metric), ELM (see section 4.3), or VSC: all these metrics increase as daylighting increases and they all showed a higher correlation compared to DA, sDA, cDA, and UDI

- such lower correlation shown by the sDA metric, compared to other metrics, seems somewhat contradictory with respect to the finding from Reinhart et al. [78-79], who observed that sDA "*reproduced the student assessments of the daylit area in a space more reliably than the other tested daylight availability metrics*". However, the goal of these studies was to find the most reliable metric in describing the portion of space 'sufficiently lit by daylight, while in the present study students were asked to judge the global daylighting amount in the classroom, or specifically on the workplane surfaces
- $UDI_{100\text{-}3000}$ show a lower correlation compared to the DA group, probably because its definition, which is based on two thresholds (frequency of how often illuminance values lie in the range 100-3000 lx)
- 'blind_closed' shows the lowest correlation, except for the factor 'view out quality' (same correlation as DF_m and ALE); the correlation was found non-significant for factors one ('daylight quantity') and two ('visual performance')
- among geometric parameters, the VSC shows the best correlation, while 'room-depth' shows a non-significant correlation for all factors except for factor 'window quality'.

Generally, all daylight metrics showed a significant correlation with student responses for all the factors. This is in line with the outcome described in Zomorodian et al [35]. Exceptions are 'close blinds' (which is not a standardized metric, rather being a descriptive indicator).

Overall, moderate to weak correlations were found between the subjective and the objective measures [80].

This is not surprising, given the results of some previous studies [81-82] that reported a difficulty in correlating the evaluation of a daylit space from the occupants to objective metrics. Previous results indicate that correlations between daylight performance indexes and users' opinions is not always observed: Bellia et al. [81] reported that "*The comparison among measured data, workers' opinions and UDI and DGP demonstrates that not always limit values of these parameters well explain human feelings and underlines how it is difficult to describe human response to light stimuli trough synthetic parameters*". In the same line, Korsavi et al. [22] compared subjective responses and simulation results and noted that non-daylit areas or sun-lit areas defined by dynamic metrics did not necessarily cause visual discomfort. They suggest that some other factors (e.g., personal factors as mood or expectations, or environmental factors as type of view out, configurations of windows) can affect the relationship between subjective ratings and daylight metrics. The present results encourage further investigations on this topic and highlight the importance of not relying only on objective parameters to define the human experience of the daylit environment. On the other hand, the above-mentioned study from Zomorodian et al. [35] shows 'strong' correlation between objective daylight metrics and subjective responses.

Among daylight metrics, the higher correlation was observed for metrics that describe the daylight provision in a space in absolute terms (DF_m and ALE), while a lower correlation was observed for 'metrics with one threshold, which describe the daylight provision in terms of frequency of a given performance (DA, cDA, $sDA_{300,50\%}$), and even lower for $UDI_{100,3000}$, which is a metric with 2 thresholds. This low performance shown by $UDI_{100\text{-}3000}$ is somewhat surprising, as the two thresholds used in the metric (100 lx and 3000 lx) might in principle fit well with the bipolar scales used for the questions in the survey, according to which a score of 3 is an acceptable performance (daylight amount, daylight comfort and so forth), while a score of 4 is 'high' (and 5 'too high') and a score of 2 is 'low' (and 1 'too low').

Consequently, it seems that quantifying the absolute daylight amount in a room can be a better indicator to account for subjective perceptions expressed by students. If on the one hand the DF_m is labeled as an 'obsolete' concept in favor of climate-based metrics, on the other hand the ALE is a climate-based metric that has been progressively abandoned within the progress of CBDM research. It could be useful to include the ALE in recommendations and protocols, and new research should be undertaken to set reference benchmark values for the qualification of a daylit space.

Moreover, all daylight metrics show the same trend, with the highest correlation for factor five ('view out quality') and then for factor three ('daylight quality'). Surprisingly, correlation showed lower values of the Spearman's ρ-coefficient for factors concerned with the daylight amount in the considered room (factor 1: 'daylight quantity') or on the visual task areas (factor two: 'visual comfort/performance'), that is to say the quantitative parameters more directly concerned with the definition of daylight metrics. Consequently, the final acceptance/perception expressed by the students seems to be governed by a more complex set of parameters and metrics, concerned with both quantitative and qualitative aspects.

As for the circadian metrics, EML and the $E_{v>1600}$ show a higher correlation than daylight metrics for factors one, two and three ('daylight quantity', 'daylight comfort/performance', and 'daylight quality'); the opposite applies for factors four and five ('view out quality, 'window quality'). Both EML and the $E_{v>1600}$ rely on the vertical illuminance at eye-level: hence, this quantity seems more sensitive than metrics based on horizontal workplane illuminance in describing the daylight perception expressed by the students. This highlights that the design of high-quality learning spaces, which yield higher satisfaction among students, should not solely rely on the compliance with objective metrics. Moreover, among these latter, metrics based on vertical illuminance should be included along with workplane illuminance.

4.2.3 RQ2: can a classroom noncompliant on daylight metrics/criteria be positively judged by students and vice versa?

To address this RQ, Fig. 8 plots the average scores calculated for the five factors versus the daylight amount in each classroom, quantified through the $sDA_{300,50\%}$. Considering that bipolar scales were used for the questionnaire, where score

3 represents an 'acceptance' condition, an area comprising the scores 2.5 and 3.5 is also highlighted in the graph.

The results do not show a univocal connection between daylight quantity and student subjective responses. However, some trends emerge: factor two ('daylight performance') showed the highest scores in all classrooms, while factor five ('view out quality') the lowest scores in most classrooms (6 out of 8); factors one ('daylight quantity') and three ('daylight quantity') show a similar trend, with higher scores more frequent for factor three.

The most surprising finding was observed for rooms with opposite features, which result in a quite different daylight provision. TUR-1 is the classroom with the highest daylight provision and the only one able to meet all the daylight criteria/requirements, while CAT does not comply with the WFR ≥ 0.125 requirement and has a low daylight amount compared to all requirements. TUR-1 and CAT received on average the same scores (around 3.5) on factor one ('daylight amount') and very similar on factor two ('visual performance'). It seems that students of classroom CAT show a good acceptance of the daylight conditions across the space. Clearly, other psychological aspects influence the scores expressed by the students [81-83]. The classroom CAT is in an historical building, close to the sea in a wonderful island (Ortigia), with a large portion of sky seen through the window: these aspects can influence the student mood and consequently their evaluation of daylighting in the classroom. An earlier DAYKE-Europe investigation highlighted how factors such as the sky condition and distance from windows had an impact on mood and comfort reported by students [36]: both campaigns in CAT occurred in clear sky conditions. To a slightly lower extent, the same trend was also observed for the other two classrooms with the lowest $sDA_{300,50\%}$: both VEN ($sDA_{300,50\%} = 0\%$) and NAP-2 ($sDA_{300,50\%} = 3.7\%$) show scores between 2.5 and 3 on factors one, two and three.

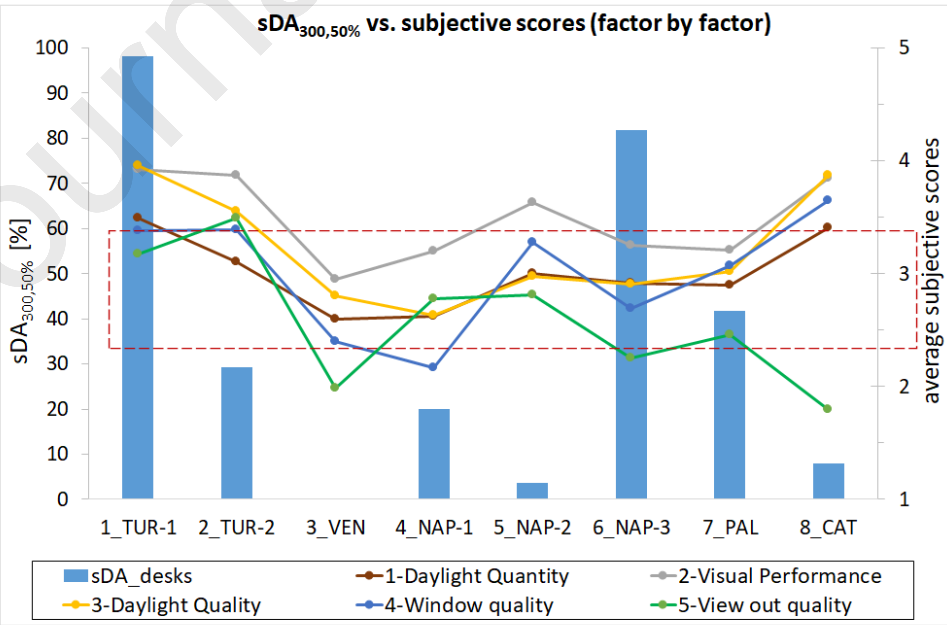


Fig. 8. Average subjective answers vs. $sDA_{300,50\%}$ for the five factors (1: daylight quantity; 2: visual performance; 3: daylight quality; 4: window quality; 5: view out quality).

4.3 Correlation between objective circadian metrics and subjective responses from students

4.3.1 Objective results from ALFA simulations

The results that were obtained from ALFA simulations are shown in Fig. 9. As explained in Section 3.2.2, these simulations were run for the days when the DAYKE-Italy survey was administered, through point-in-time analyses rather than annual analyses. Both the EML and the melanopic ratio are plotted for the two DAYKE campaigns: spring 2019 session (eight classrooms) and fall-winter 2019-2020 session (five classrooms). Two reference lines are also plotted to show the minimum requirements set by the WELL protocol (EML ≥ 120 lx) and by the CHPS protocol (EML ≥ 250 lx).

The following main considerations can be drawn:

- all classrooms comply with the WELL requirement (EML ≥ 120 lx) in the spring session, independently of the sky conditions, while EML significantly drop in the fall-winter session, with NAP-2 (all sky conditions) and PAL and CAT (overcast sky) not complying with the requirement
- considering the stricter requirement set by the CHPS protocol, three classrooms are barely compliant or not compliant: VEN, NAP-1, and CAT
- the highest ELM is observed in classrooms with higher daylight provision, namely TUR-1, TUR-2, and PAL
- an interesting feature emerges by comparing the three classrooms in Naples: they have the same materials, but different positions inside the building, in terms of orientation and floor. NAP-2 is located on the fifth floor, thus being more exposed to a direct view of the sky (VSC = 0.36) and show a melanopic ratio R = 0.82 in clear sky and R = 0.78 in overcast sky; differently, NAP-1 is located on the 2nd floor, thus being more exposed to a quite lower view of the sky (VSC = 0.20) and mostly 'seeing' the yellow façade of the courtyard: as a result, the melanopic ratio R is 0.40 in clear sky and 0.52 in overcast sky. This shows the impact of the color of the façade, compared to the sky, on the melanopic content of the visible daylight admitted into the space.

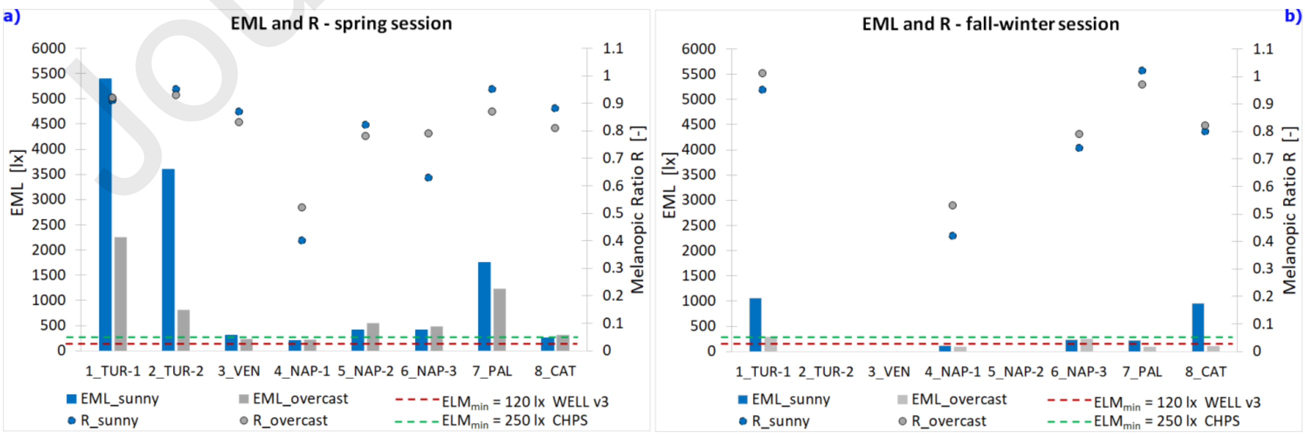


Fig. 9. Results from ALFA point-in-time simulations for ELM and melanopic ratio R: (a) spring session; (b) fall-winter session.

4.3.2 *RQ3: do circadian metrics based on the EML (equivalent melanopic lux) fit the subjective responses expressed by students?*

Table 6 reports the Spearman's ρ-correlation coefficients between the objective circadian metrics and the factors extracted from subjective responses. These correlation coefficients are also graphically visualized in Fig. 10 to allow the reader an easier comparison among the various metrics considered.

Table 6.
Spearmans' ρ-correlation coefficients and significance between daylight metrics and factors extracted from subjective responses.

Circadian metrics	daylight quantity	visual performance	daylight quality	window quality	view out quality
melanopic ratio R	0.117*	0.122***	0.199***	0.257***	0.324**
EML	0.330***	0.257***	0.400***	0.162***	0.323***
$E_{v,eye}$	0.284***	0.269***	0.354***	0.214***	0.182***

*** The correlation coefficient is significant at the p<.001 level
** The correlation coefficient is significant at the p<.01 level
* The correlation coefficient is significant at the p<.05 level.

Results show that all the three circadian metrics show a significant correlation with all the five factors extracted from subjective responses.

Fig. 10 graphically visualizes the trends of the correlation between objective circadian metrics and subjective judgments expressed by the students. As shown in the Figure, EML seems to show a higher correlation than DF_m and ALE, thus being the metric with the highest correlation at all (except for factor 'view out quality').

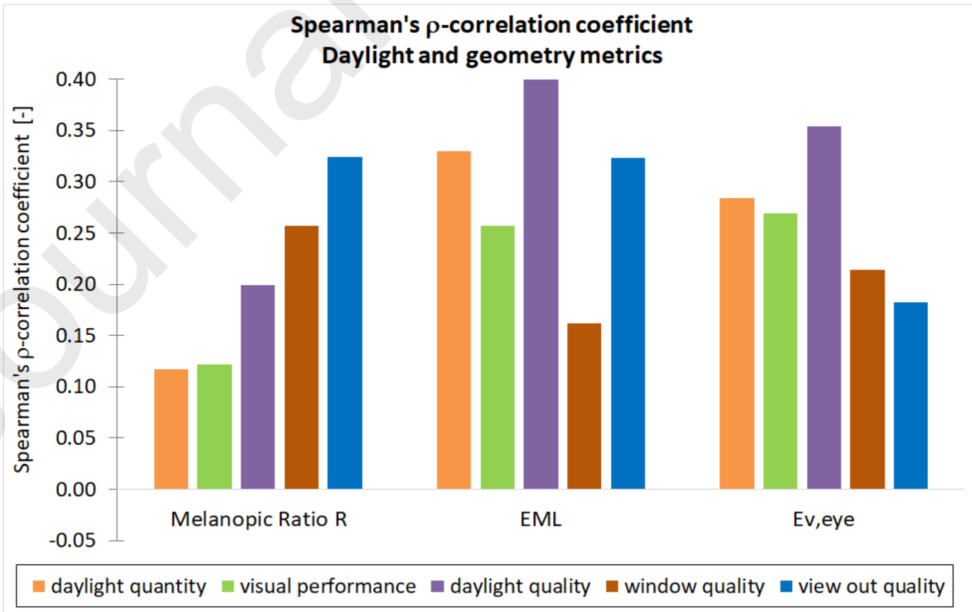


Fig. 10. Spearman's ρ-coefficients for the correlation between circadian metrics and the five factors (1: daylight quantity; 2: visual performance; 3: daylight quality; 4: window quality; 5: view out quality).

The ALFA simulation tool was used to calculate the circadian metrics EML and the melanopic ratio. Since it was not possible to measure the spectral reflectance of the space surfaces in each classroom, it was decided to pick the materials from the library of the program. Clearly, this introduces a bias, compared to a realistic modeling of the real materials used in the classrooms. However, ALFA provides a quite huge library of materials, which makes it possible to select materials close to the ones observed in the real spaces. This was considered acceptable, considering the purpose of the paper, which was to correlate objective metrics and subjective responses. Many materials are quite typical (wooden chairs, plasters, glazing) and are reasonably used in several spaces, as the ones considered in the study.

However, a validation of the calculation process was carried out for two classrooms: TUR-1 and TUR-2. For this space, the spectral reflectance of each surface in the space (walls, ceiling, floor, desks, frame) and outside the space (grass, sidewalks, buildings ahead) was measured through a contact spectro-photometer Minolta CM600d (measurement range: 400-700 nm; measurement sensitivity: 10 nm; error: ±5%). These spectral distributions were imported into ALFA as new, customized materials, and simulations were run to calculate the circadian metrics and to compare them to the values that had been obtained by picking in the ALFA library the closest materials to the materials observed in the classrooms. Table 7 shows the results that were obtained following the two approaches (ALFA library material vs. spectro-photometer measurements). The difference in the EML and R values obtained remains below a peak value of 8% (TUR-2, winter session, clear sky) and below 4.5% for all the other cases. Such a small difference would not have any impact on the statistical correlations between subjective responses and objective metrics calculated through ALFA (independently of the approach adopted).

Table 7.
Circadian metrics (EML and R) calculated through ALFA simulations by picking materials from the ALFA library or by creating new materials in ALFA using spectrophotometer measurements.

classroom	metric					
	EML [lx]			R [-]		
	ALFA materials	spectro-photometer	*relative difference [%]*	ALFA materials	spectrophoto-meter	*relative difference [%]*
	spring session					
TUR-1_clear	5391	5243	*-2.75*	0.91	0.95	*4.40*
TUR-1_overcast	2255	2317	*2.75*	0.92	0.94	*2.17*
TUR-2_clear	3596	3879	*7.87*	0.95	0.88	*-7.37*
TUR-2_overcast	802	827	*3.12*	0.93	0.87	*-6.45*
	winter-fall session					
TUR-1_clear	1053	1100	*4.46*	0.95	0.94	*-1.05*
TUR-1_overcast	279	267	*-4.30*	1.01	1.02	*0.99*

4.4 Potential energy savings from daylight and correlation to daylight metrics

4.4.1 Energy demand for lighting from DIVA simulations

The energy demand for lighting (LENI values) for existing lighting systems (fluorescent tubes) are shown in Fig. 11, where LENI values for manual and photo-dimming controls are plotted. In the graph, energy savings (ΔLENI) and $sDA_{300,50\%}$, values are also plotted for each classroom, to allow energy consumption and energy savings to be compared to the daylight provision in the room. A line for the reference $LENI_{max}$ of 19 kWh/(m^{2}yr) is also plotted [73].

The following consideration can be drawn:

- for manual controls, the highest LENI values are observed for NAP-3 (LPD = 9.2 W/m^2) and TUR-1, which are the two spaces with the highest lighting power density installed (LPD = 9.2 W/m^2 and LPD = 10.8 W/m^2, respectively)
- on the other hand, the lowest LENI values were observed for TUR-1 and for NAP-1, this latter the room with the lowest LPD (4.3 W/m^2)
- for photo-dimming controls, classrooms with higher $sDA_{300,50\%}$ yield the highest energy saving. This is the case of TUR-1 ($sDA_{300,50\%}$ = 98.2%; ⊗LENI = -52.7%) and NAP-3 ($sDA_{300,50\%}$ = 81.7%; ⊗LENI = -21.0%). Differently, TUR-2 shows a saving of -30.3% (second best), despite a moderate $sDA_{300,50\%}$ (29.2%).
- on the other hand, classrooms with lower $sDA_{300,50\%}$ yield the lowest saving. This is particularly evident for VEN, where $sDA_{300,50\%}$ = 0 is observed, with a negligible saving of -1.2%

It also emerged that TUR-1 is the only classroom where the LENI drops below the maximum recommended value of 19 kWh/m^{2}yr (with photodimming controls). The other classrooms show LENI values over this limit also in the presence of daylight responsive controls. This is due to the combination of two factors: the presence of lighting systems equipped with fluorescent tubes and a sometimes-excessive LPD. To decrease the consumption, a relamping intervention where fluorescent lighting systems were replaced with LED lighting systems should be carried out, consistently with what is shown by Doulos et at. [13].

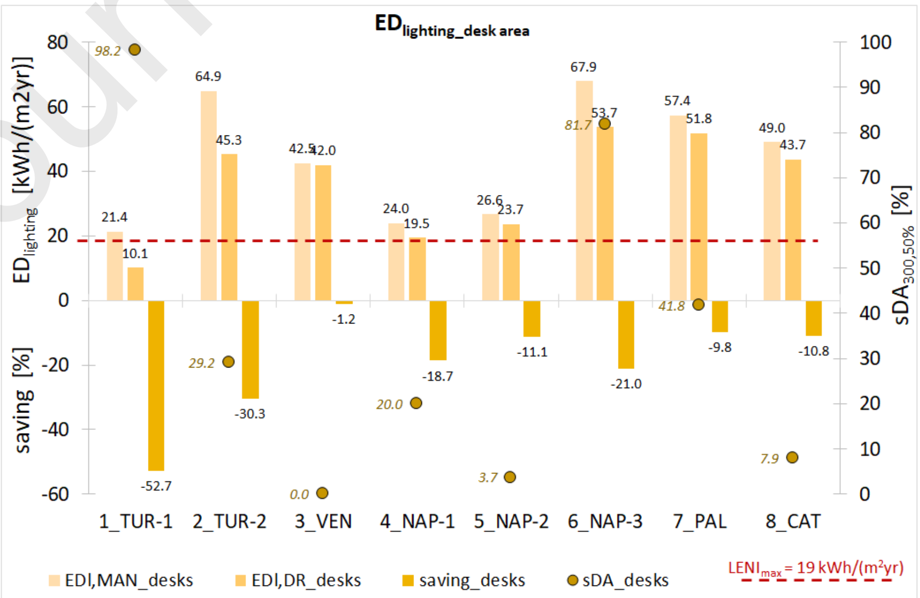


Fig. 11. Results from DIVA simulations in terms of energy demand for lighting ($ED_{lighting}$ = LENI index).

4.4.2 RQ4: is there a correlation between energy use/saving and some daylight metric/criterion?

Table 8 reports the Spearman's ρ-correlation coefficients between the energy saving and daylight/circadian metrics, all calculated through DIVA simulations.

The correlation coefficients show that apart from the melanopic ratio (non-significant correlation), all other metrics have a significant, yet moderate, correlation with the energy saving: among them, the highest correlation was shown by EML (correlation coefficient of -0.483), closely followed by DA, $sDA_{300,50\%}$, and cDA (-0.437).

Table 8.
Spearmans' ρ-coefficient and significance for daylight and circadian metrics and energy saving.

	DF_m	DA	sDA	cDA	UDI	Blind Close	ALE	VSC	room depth	R ratio	EML	E_{v_eye}
saving	-.304***	-.437***	-.436***	-.437***	-.401***	.303***	-.236***	-.224***	.401***	0.007	-.483***	-.675***

*** The correlation coefficient is significant at the p<.001 level

5. Conclusions

Within the DAYKE-Italy project, a thorough investigation on the daylight quantity and quality in a sample of Italian universities was carried out. This consisted of a combined approach: an ad-hoc survey that was administered to students to investigate how they perceive daylight conditions in their classroom, and numerical simulations to calculate a set of objective metrics (daylight, circadian, and energy-related), with the aim of correlating subjective and objective findings. A sample of 542 questionnaires was collected through two sessions (in spring, April-June 2019, and in fall-winter, November 2019 - January 2020). The following set of daylight metrics was calculated through DIVA-for-Rhino simulations: average and spatial daylight factor (DF_m and sDF), daylight autonomy DA, continuous daylight autonomy cDA, spatial daylight autonomy $sDA_{300,50\%}$, annual sunlight exposure $ASE_{1000,250}$, percent of time when vertical eye-level is over 1600 lx $E_{v>1600}$, $F_{DGP>0.40}$, annual light exposure ALE. As for circadian metrics, equivalent melanopic lux EML and melanopic ratio R were calculated through ALFA simulations; as for energy-related metrics, the annual energy demand for lighting in the presence of manual and daylight responsive photo-dimming controls were calculated again through DIVA.

In short, the study relies on the following assumptions: (i) daylight and energy metrics were calculated using DIVA, through annual simulations (therefore they are 'annual' metrics); DF_m is an exception, as it was calculated through DIVA simulations, but is a constant value during the course of a year; (ii) circadian metrics were calculated using ALFA, through point-in-time simulations (for the time-steps when experimental campaigns were carried out); (iii) subjective scores were collected through two campaigns, in the same classrooms but with different students. The correlation results which were obtained are therefore valid under these assumptions. Changing one or more of such assumptions might lead to different correlations.

The following main consideration emerged from descriptive and statistical analyses:

- all the daylight metrics considered in the study showed a significant correlation with the student subjective judgments; this is in line with the results from a similar study from Zomorodian et al [35]
- among daylight metrics, the highest correlation was observed for metrics that describe the absolute daylight provision in a room, namely the average daylight factor DF_m and the Annual Lighting Exposure ALE; a lower correlation was observed for 'threshold metrics', i.e. metrics which describe the daylight provision in a scape in terms of frequency of how often illuminance lies in a given interval (DA, cDA, $UDI_{100\text{-}3000}$) or portion of space where a DA criterion is reached ($sDA_{300\text{-}50\%}$)
- the circadian metric EML, which accounts for the vertical illuminance at eye-level and for the spectral distribution of daylight (entering through windows as well as reflected by surfaces) showed a good correlation with the student subjective judgments, even higher than daylight metrics based on the horizontal workplane; it is probable that other metrics that account for the luminance distribution in occupants' visual field, such as the average wall luminance, or the cylindrical illuminance, would also show a good correlation [84]. There is an increasing need for lighting regulations that include vertical illuminances or other related metrics, beside the consolidated workplane illuminance
- it was not possible to establish a univocal correspondence between objective metrics and subjective respondents: classrooms with high daylight performance in objective terms (and compliance with daylight criteria or recommended references) and classrooms with quite low daylight performance were judged practically with the same scores; this shows that spaces non-compliant with minimum standard requirements can be positively judged and accepted by students, since a high number of parameters have an impact on user mood, comfort and final acceptance of a space (these may involve aesthetical and architectural features of the classroom or even of the whole building, especially when the classroom is located in an historical building, as in the case of CAT and VEN)
- the energy demand for lighting in the classrooms, all equipped with traditional fluorescent lighting systems, is quite high. It gets reduced in the presence of high daylight provision and photo-dimming sensors. Nevertheless, a relamping intervention with the installation of more efficient LED lighting systems seems to be necessary to reduce the energy demand for lighting below a target value of 19 kWh/(m^2yr)
- all objective metrics (apart from the melanopic ratio) show a significant, yet moderate, correlation with the energy saving: the highest correlation was shown by EML, closely followed by DA, $sDA_{300,50\%}$, and cDA

Consistently with the earlier part of the DAYKE research, the main merit of the study lies in the thorough investigation concerning knowledge, perception, and education of daylighting in Europe, replicated in the Italian context. To the authors' knowledge, no such attempt has been performed so far through such a multiple investigation area approach.

The present study is intended to cover the main topics nowadays concerned with daylight in buildings: visual comfort and performance associated with daylight, health (non-visible effects of daylight), and energy saving. To do that, a holistic approach was adopted, which included objective metrics (daylight, circadian, and energy-related) and statistically correlated them with subjective responses from students. Comparing daylight metrics to subjective judgments is not new: a similar study has been recently presented by Zomordian et al. [35]: however, it certainly was useful to replicate the approach to a quite different context (Texas vs. Italy) to expand the validation of daylight metrics through subjective judgments. Comparing the student subjective assessments to a circadian metric (namely, the equivalent melanopic lux ELP) is, to the Authors' knowledge, a new step.

It would be interesting to replicate the study adopting a longitudinal design, in which subjective responses are collected for each classroom by the same students more than once during the school year, to monitor the trends of the correlations between students' perceptions and daylight metrics over a longer time period and analyze if the correlations between simulation results and subjective assessments would be consistent with the ones obtained in the present study.

It is the Authors' opinion that the conclusions may be transferable to other types of buildings, such as offices and factories, as the correlation between daylight/circadian metrics and user responses also interests other types of space, uses, and activities. Daylighting can enhance performance, comfort and productivity not only for children in schools, but also for adults in office buildings.

References

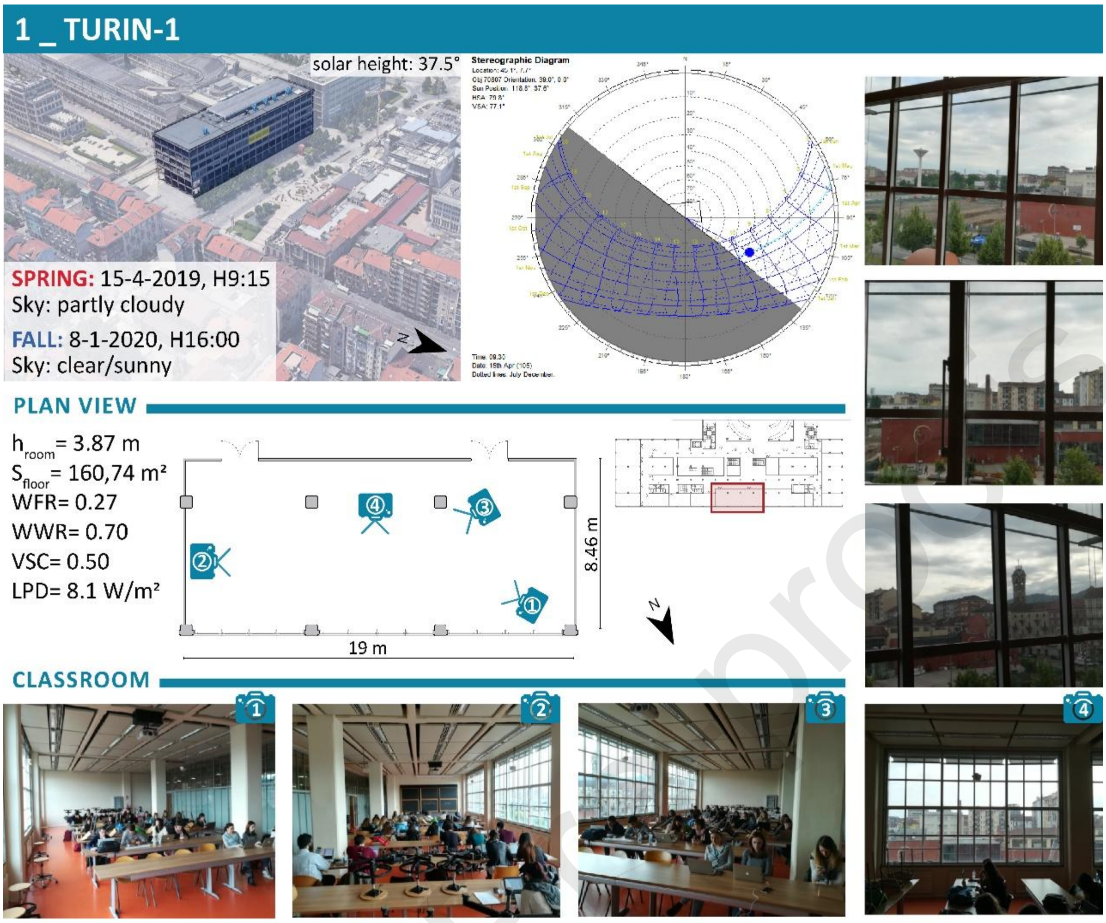
[1] Society of Light and Lighting (SLL). Lighting Guide 5: Lighting for education. Distributed through the Chartered Institution of Building Services Engineers (CIBSE), Watford, UK, 2011.
[2] Mirrahimi, S.; Lukman, N.; Ibrahim, N.; Surat, M. Effect of daylighting on student health and performance. Proc. of the 15th International Conference on Mathematical and Computational Methods in Science and Engineering, Kuala Lumpur, Malaysia, 2–4 April 2013; WESEAS Press: Grete, Greece, 2013; pp. 127–132.
[3] V. Costanzo, G. Evola, L. Marletta. A Review of Daylighting Strategies in Schools: state of the Art and Expected Future Trends. Buildings 7 (2017) 41, https://doi.org/10.3390/buildings7020041.
[4] M. Knoop, O. Stefani, B. Bueno, B. Matusiak, R. Hobday, A. Wirz-Justice, K. Martiny, T. Kantermann, M.P.J. Aarts, N. Zemmouri, S. Appeltk, and B. Norton. Daylight: What makes the difference? Lighting Res. Technol. 0 (2019) 1–20, https://doi.org/10.1177/1477153519869758.
[5] F. De Luca. Daylight in schools guidance. Tallinn University of Technology, Department of Civil Engineering and Architecture, 2020.
[6] Kuller, R.; Lindsten, C. Health and behaviour of children in classrooms with and without windows. J. Environ. Psychol. 12 (1992) 305–317.
[7] M. Winterbottom, A. Wilkins. Lighting and discomfort in the classroom. Journal of Environmental Psychology 29 (2009) 63–75, https://doi.org/10.1016/j.jenvp.2008.11.007.
[8] A. Michael, C. Heracleous, Assessment of natural lighting performance and visual comfort of educational architecture in Southern Europe: the case of typical educational school premises in Cyprus, Energy Build. 140 (2017) 443-457, https://doi.org/10.1016/J.ENBUILD.2016.12.087.
[9] Boyce, P.; Hunter, C.; Howlett, O. The Benefits of Daylight through Windows; Lighting Research Center, Rensselaer Polytechnic Institute, Troy: New York, NY, USA, 2003.
[10] M.G. Figueiro, J.A. Brons, B. Plitnick, B. Donlan, Leslie, M.S. Rea. Measuring circadian light and its impact on adolescents. Lighting Res. Technol. 2011; 43: 201–215, https://doi.org/10.1177/1477153510382853.
[11] A. Pellegrino, S. Cammarano, V. Savio. Daylighting for Green schools: A resource for indoor quality and energy efficiency in educational environments. Energy Procedia 78 (2015) 3162–3167.
[12] Building Research Establishment Ltd. (BRE). Report describing initial literature review on circadian lighting. BRE Client Report B137170-01, Distributed through the Chartered Institution of Building Services Engineers

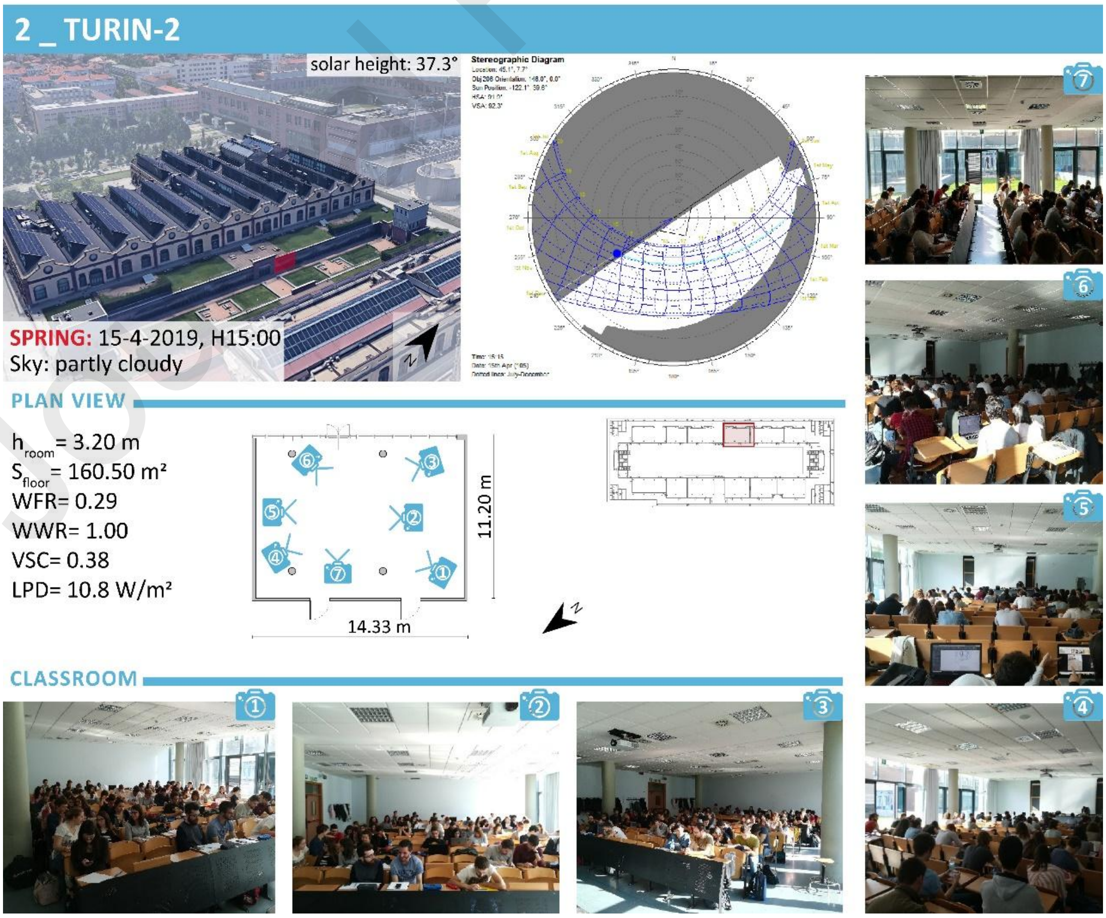
(CIBSE), Watford, UK, 2017.
[13] L.T. Doulos, A. Kontadakis, E.N. Madias, M. Sinou, A. Tsangrassoulis. Minimizing energy consumption for artificial lighting in a typical classroom of a Hellenic public school aiming for near Zero Energy Building using LED DC luminaires and daylight harvesting systems. Energy & Buildings 194 (2019) 201–217, https://doi.org/10.1016/j.enbuild.2019.04.33.
[14] S. Safranek, J.M. Collier, A. Wilkerson, R.G. Davis. Energy impact of human health and wellness lighting recommendations for office and classroom applications. Energy & Buildings 226 (2020) 110365, https://doi.org/10.1016/j.enbuild.2020.110365.
[15] M. Bonomolo, C. Baglivo, G. Bianco, P.M. Congedo, M. Beccali. Cost optimal analysis of lighting retrofit scenarios in educational buildings in Italy. Energy Procedia, 126 (2017) 171-178, https://doi.org/10.1016/10.1016/j.egypro.2017.08.137.
[16] M. Beccali, L. Bellia, F.M. Fragliasso. Bonomolo, G. Zizzo , G. Spada,. Assessing the lighting systems flexibility for reducing and managing the power peaks in smart grids. Applied Energy 268 (2020) 114924, https://doi.org/10.1016/j.apenergy.2020.114924.
[17] L. Heschong, Roger L. Wright & Stacia Okura (2002) Daylighting Impacts on Human Performance in School, Journal of the Illuminating Engineering Society, 31:2, 101-114, https://doi.org/10.1080/00994480.2002.10748396.
[18] D.A. Chi, D. Moreno, J. Navarro. Correlating daylight availability metric with lighting, heating and cooling energy consumptions. Building and Environment 132 (2018) 170–180, https://doi.org/10.1016/j.buildenv.2018.01.048.
[19] T. Srisamranrungruang, K. Hiyama. Balancing of natural ventilation, daylight, thermal effect for a building with double-skin perforated facade (DSPF). Energy & Buildings 210 (2020) 109765, https://doi.org/10.1016/j.enbuild.2020.109765.
[20] I. Konstantzos, S.A. Sadeghi, M. Kim, J. Xiong, A. Tzempelikos. The effect of lighting environment on task performance in buildings–a review. Energy & Buildings (2020) 110394, https://doi.org/10.1016/j.enbuild.2020.110394.
[21] F. Nocera, A. Lo Faro, V. Costanzo, C. Raciti. Daylight Performance of Classrooms in a Mediterranean School Heritage Building. Sustainability 2018, 10, 3705; https://doi.org/10.3390/su10103705.
[22] S.S. Korsavi, Z.S. Zomorodian, M. Tahsildoost. Visual comfort assessment of daylit and sunlit areas: A longitudinalfield survey in classrooms in Kashan, Iran. Energy and Buildings 128 (2016) 305–318.
[23] P. Bakmohammadi, E. Noorzai. Optimization of the design of the primary school classrooms in terms of energy and daylight performance considering occupants’ thermal and visual comfort. Energy Reports 6 (2020) 1590–1607.
[24] R. Delvaeye, W. Ryckaert, L. Stroobant, P. Hanselaer, R. Klein, H. Breesch. Analysis of energy savings of three daylight control systems in a school building by means of monitoring. Energy and Buildings 127 (2016) 969–979, http://dx.doi.org/10.1016/j.enbuild.2016.06.033.
[25] Z.S. Zomorodian, M. Tahsildoost. Assessment of window performance in classrooms by long-term spatial comfort metrics. Energy and Buildings 134 (2017) 80–93, http://dx.doi.org/10.1016/j.enbuild.2016.10.018.
[26] I.L. Wong. A review of daylighting design and implementation in buildings. Renewable and Sustainable Energy Reviews 74 (2017) 959–968, http://dx.doi.org/10.1016/j.rser.2017.03.061.
[27] V. Costanzo, G. Evola, L. Marletta, F. Pistone Nascone, Application of climate based daylight modelling to the refurbishment of a school building in Sicily. Sustainability 10(8) (2018) 2653.
[28] A.A.Y. Freewan, J.A. Al Dalala. Assessment of daylight performance of Advanced Daylighting Strategies in Large University Classrooms; Case Study Classrooms at JUST. Alexandria Engineering Journal 59 (2020), 791–802, https://doi.org/10.1016/j.aej.2019.12.049.
[29] W. Wu, E. Ng A review of the development of daylighting in schools. Lighting Research & Technology 35(2) (2003) 111–125, https://doi.org/10.1191/1477153503li072oa.
[30] N. Castilla, C. Llinares, J.M. Bravo, V. Blanca. Subjective assessment of university classroom environment. Building and Environment 122 (2017) 72-81, http://dx.doi.org/10.1016/j.buildenv.2017.06.004.
[31] R.M. Baloch, C.N. Maesano, J. Christoffersen, C. Mandin, E. Csobod, E. de Oliveira Fernandes, I. Annesi-Maesano, and on behalf of the Sinphonie Consortium. Daylight and School Performance in European Schoolchildren. International Journal of Environmental Research and Public Health, 18(1) (2021), 258, doi: https://doi.org/10.3390/ijerph18010258
[32] Q. Liu, Z. Huang, Z. Li, M.R. Pointer, G. Zhang, Z. Liu, H. Gong, Z. Hou. A Field Study of the Impact of Indoor Lighting on Visual Perception and Cognitive Performance in Classroom. Applied Sciences, 10(21) (2020) 7436, doi: https://doi.org/10.3390/app10217436.
[33] P. Ricciardi, C. Buratti. Environmental quality of university classrooms: Subjective and objective evaluation of the thermal, acoustic and lighting comfort conditions. Building and Environment 127 (2018) 23-36, https://doi.org/10.1016/j.buildenv.2017.10.030.
[34] V. De Giuli, O. Da Pos, M. De Carli. Indoor environmental quality and pupil perception in Italian primary schools. Building and Environment 56 (2012) 335-345, doi: https://doi.org/10.1016/j.buildenv.2012.03.024.
[35] Z.S. Zomorodian, M. Tahsildoost. Assessing the effectiveness of dynamic metrics in predicting daylight availability and visual comfort in classrooms. Renewable Energy 134 (2019) 669-680.

[36] F. Giuliani, N. Sokol, V.R.M. Lo Verso, R.J.A.V. Viula F. Caffaro, B. Paule. A. Diakite, Y. Sutter. A study on daylighting knowledge and education in Europe. Architectural Science Review (2019) in press, https://doi.org/10.1080/00038628.2019.1675042.
[37] F. Giuliani, N. Sokol, R.J.A.V. Viula, V.R.M. Lo Verso, H. Coch Roura, F. Caffaro First outcome of an investigation about daylighting knowledge and education in Europe. Proc. of International Conference LuxEuropa 2017, Ljubljana, Slovenia, September 2017.
[38] F. Giuliani, N. Sokol, V.R.M. Lo Verso, R.J.A.V. Viula F. Caffaro, B. Paule. A. Diakite, Y. Sutter. Daylighting education in practice. Verification of a new goal within a European knowledge investigation. Proc. of. PLEA International Conference, Hong Kong, December 10-12, 2018.
[39] V.R.M. Lo Verso, F. Giuliani, F. Caffaro, F. Basile, F. Peron, T. Dalla Mora, L. Bellia, F. Fragliasso, M. Beccali, M. Bonomolo, F. Nocera, V. Costanzo. A survey on daylighting education in Italian universities. Knowledge of standards, metrics and simulation tools. Journal of Daylighting 8 (2021) 36-49, doi: https://doi.org/10.15627/jd.2021.3.
[40] Italian Law Decree December 18, 1975. Upgraded technical standard on educational building, including didactic, building and urban functions, to be applied in educational building works (*in Italian*), Rome.
[41] Italian Technical Standard UNI 10840:2007. Light and lighting – Educational buildings – General criteria for artificial and natural lighting (*in Italian*). Distributed through the Ente Italiano di normazione, Milan.
[42] Law Decree 11 October 2017. Criteri ambientali minimi per l'affidamento di servizi di progettazione e lavori per la nuova costruzione, ristrutturazione e manutenzione di edifici pubblici (*in Italian*). Rome
[43] M. Nigra, V.R.M. Lo Verso, M. Robiglio, A. Pellegrino, M. Martina. 'Re-coding' environmental regulation – a new simplified metric for daylighting verification during the window and indoor space design process. Architectural Engineering and Design Management (2021), paper 1941738, doi:: https://doi.org/10.1080/17452007.2021.1941738.
[44] Green Building Council Italy (2016). LEED NC 2009 Italy - Green Building: new constructions and refurbishments (*in Italian*). Upgrade 2016 (withdrawn in 2019).
[45] J. Mardaljevic. Climate-Based Daylight Analysis. CIE (Commiss. Internat. de l'Eclairage) Report 3–26, 2008.
[46] CIE (Commission International de l'Eclairage). Publication CIE 157: Control of damage to museum objects by optical radiation. Vienna, Austria, 2004.
[47] J. Mardaljevic. Examples of climate-based daylight modelling. Paper presented at the CIBSE National Conference:Engineering the Future, London, UK, 2006.
[48] C.F. Reinhart, J. Mardaljevic, Z. Rogers. Dynamic daylight performance metrics for sustainable building design. Leukos 3 (2006) 7–31.
[49] IES Daylight Metrics Committee (2012). IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE); Daylight Metrics Committee. Approved Method IES LM-83-12; Illuminating Engineering Society of North America: New York, NY, USA.
[50] J. Mardaljevic, M. Andersen, N. Roy, J. Christoffersen, Daylighting metrics for residential buildings. In: Proc. of 27th Session of CIE International Conference, Sun City, South Africa, 2011.
[51] J. Wienold, J. Christoffersen. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings, 38(7) (2006) 743–757.
[52] L. Giovannini, F. Favoino, V.R.M. Lo Verso, V. Serra, A. Pellegrino. GLANCE (GLare ANnual Classes Evaluation): An approach for a simplified spatial glare evaluation. Building and Environment 186 (2020) 107375.
[53] Carlucci, S., Causone, F., De Rosa, F., Pagliano, L. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. Renewable Sustainable Energy Reviews, 47 (2015) 1016–1033, https://doi.org/10.1016/j.rser.2015.03.062.
[54] T. Dalla Mora, A. Leorin, G. Nardo, N. Busatto, F. Peron, P. Romagnoni. Daylight Performances in Typical Inner Spaces with Climate-Based Daylight Modeling Approach. Proc. of 4th Building Simulation and Optimization Conference, Cambridge, UK, 2018.
[55] E. Brembilla, J. Mardaljevic. Climate-Based Daylight Modelling for compliance verification: benchmarking multiple state-of-the-art methods. Building and Environment 158 (2019) 151–164, https://doi.org/10.1016/j.buildenv.2019.04.051.
[56] USGBC - United States Green Building Council. LEED v4.1 - Building Design and Construction, 2020.
[57] UK Education Funding Agency. Baseline designs and strategies for schools in the Priority School Building Programme (PSBP). PSBP baseline designs: daylight strategy, 2014. Available at: https://www.gov.uk/government/publications/psbp-baseline-designs (last retrieved: December 13, 2020).
[58] CEN - Comité Européen de Normalisation (2018). European Standard EN 17037:2018 - Daylight in buildings. European Committee for Standardization, Brussel.
[59] S. Altomonte. Daylight for Energy Savings and Psycho-Physiological Well-Being in Sustainable Built Environments. Journal of Sustainable Development 1(3) (2008) 3-16.
[60] J. Mardaljevic, M. Andersen, N. Roy and J. Christoffersen. A framework for predicting the non-visual effects of daylight - Part II: The simulation model. Lighting Research & Technology 46(4) (2014) 388-406. http://dx.doi.org/10.1177/1477153513491873.
[61] I. Acosta, M.G. Figueiro. Analysis of circadian stimulus allowed by daylighting in hospital rooms. Light. Res.

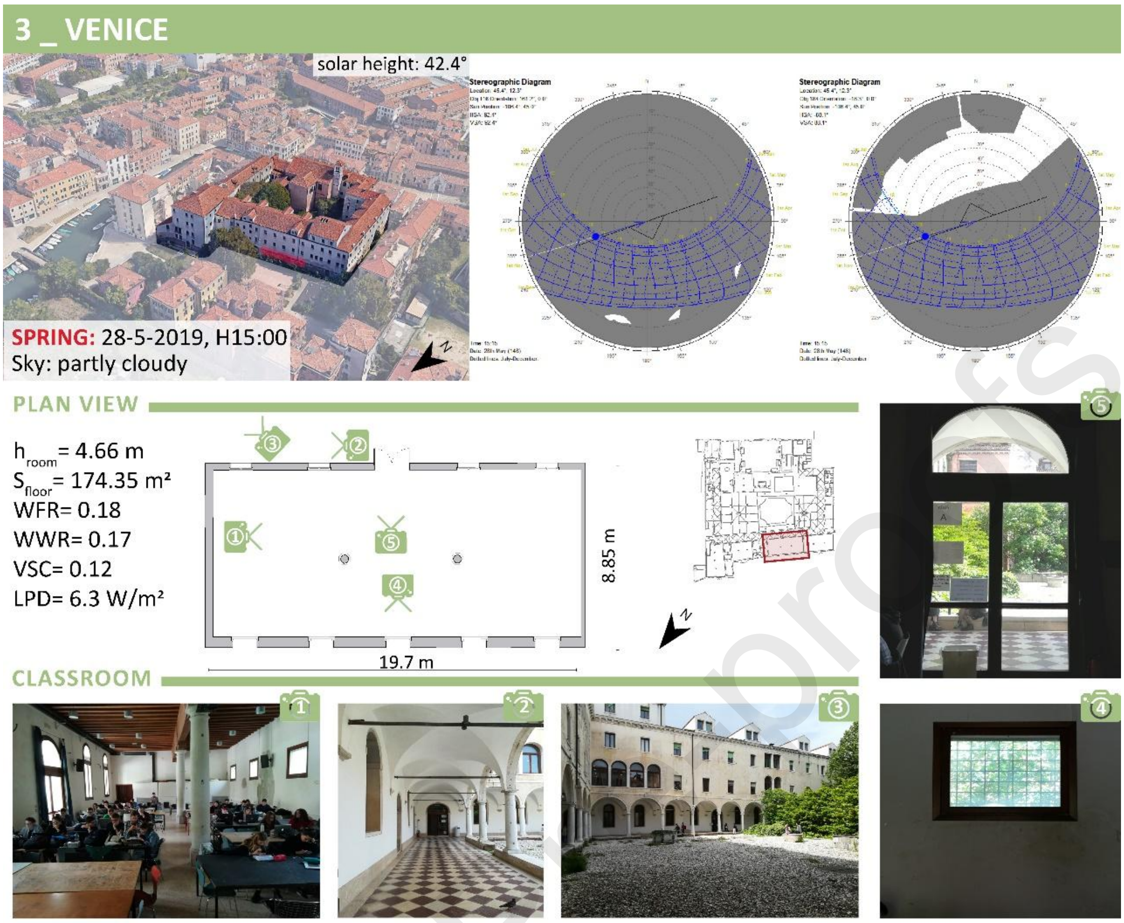
Technol. .49(1) (2017).49-61, http://dx.doi.org/10.1177/1477153515592948.
[62] Rea, M.S.; Figueiro, M.G. Light as a circadian stimulus for architectural lighting. Light. Res. Technol. 2018, 50, 497–510.
[63] Figueiro, M.G.; Kalsher, M.; Steverson, B.C.; Heerwagen, J.; Kampschroer, K.; Rea, M.S. Circadian-effective light and its impact on alertness in office workers. Light. Res. Technol. (2018) 1–13.
[64] A. Jamrozik, N. Clements, S.S. Hasan, J. Zhao, R. Zhang, C. Campanella, V. Loftness, P. Porter, S. Ly, S. Wang, B. Bauer. Access to daylight and view in an office improves cognitive performance and satisfaction and reduces eyestrain: A controlled crossover study. Building and Environment 165 (2019) 106379, http://dx.doi.org/10.1016/j.buildenv.2019.106379.
[65] N. Busatto, T. Dalla Mora, F. Peron, P. Romagnoni. Application of Different Circadian Lighting Metrics in a Health Residence. Journal of Daylighting 7 (2020) 13-24, http://dx.doi.org/: 10.15627/jd.2020.2.
[66] J. a. Enezi, V. Revell, T. Brown, J. Wynne, L. Schlangen and R. Lucas, Journal of biological rhythms 26 (2011) 314-323.
[67] R. J. Lucas, S. N. Peirson, D. M. Berson, T. M. Brown, H. M. Cooper, C. A. Czeisler, M. G. Figueiro, P. D. Gamlin, S. W. Lockley, J. B. O'Hagan, L. L. Price, I. Provencio, D. J. Skene and G. C. Brainard, Measuring and using light in the melanopsin age, Trends in Neurosciences 37(1) (2013) 1-9, http://dx.doi.org/10.1016/j.tins.2013.10.004.
[68] International WELL Building Institute. WELL v3 – The next version of the WELL building standard. 2019.
[69] CHPS - Collaborative for High Performance Schools (2019). Core Criteria, https://chps.net/chps-criteria.
[70] CIE (Commission Internationale de l'Eclairage). CIE System for Metrology of Optical Radiation for ipRGCInfluenced Responses to Light. Publication CIE S 026/E:2018, Vienna, Austria.
[71] CEN (Comité Européen de Normalisation). European Standard EN 15193-1:2017. "Energy performance of buildings - Energy requirements for lighting - Part 1: Specifications, Module M9". Brussels. 2017.
[72] CEN (Comité Européen de Normalisation),. Energy performance of buildings — Energy requirements for lighting - Part 2: Explanation and justification of EN 15193-1, Module M9. Technical Report FprCEN/TR 15193-2:2017.
[73] HM Government. Non-domestic building services compliance guide. Published by NBS, part of RIBA Enterprises Ltd, Newcastle (UK), ISBN: 978 185946 546 6. Online version, available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/453973/non_domestic_building_services_compliance_guide.pdf (last access: December 13, 2020).
[74] K. Konis. Predicting visual comfort in side-lit open-plan core zones: results of a field study pairing high dynamic range images with subjective responses, Energy and Buildings 77 (2014) 67–79.
[75] DIVA-for-Rhino: available from SOLEMMA site: https://www.solemma.com/Diva.html.
[76] ALFA: available from SOLEMMA site: https://www.solemma.com/Alfa.html.
[77] SPSS: IBM Corporation, Armonk, NY.
[78] C.F. Reinhart, D.A.Weissman. The daylit area – Correlating architectural student assessments with current and emerging daylight availability metrics. Building and Environment 50 (2012) 155-164, doi: https://doi.org/10.1016/j.buildenv.2011.10.024.
[79] C. Reinhart, T. Rakha, D. Weissman, Predicting the daylit Area - a comparison of students assessments and simulations at eleven schools of architecture, LEUKOS – Journal of Illuminating Engineer Society of North America 10 (2014) 193-206, https://doi.org/10.1080/15502724.2014.929007.
[80] H. Akoglu. User's guide to correlation coefficients. Turkish Journal of Emergency Medicine 18 (2018) 91–93. https://doi.org/10.1016/j.tjem.2018.08.001.
[81] L. Bellia, F. Fragliasso, E. Stefanizzi, Daylit offices: a comparison between measured parameters assessing light quality and users' opinions, Building and Environment 113 (2017) 92-106, https://doi.org/10.1016/j.buildenv.2016.08.014.
[82] A.D. Galasiu, J. A. Veitch. Occupant Preferences and Satisfaction with the Luminous Environment and Control Systems in Daylit Offices: A Literature Review. Energy and Buildings 38 (2006) 728–742.
[83] N. Wang, M. Boubekri. Design Recommendations Based on Cognitive, Mood and Preference Assessments in a Sunlit Workspace. Lighting Research and Technology 43 (2010) 55–72.
[84] S. Torres, V.R.M. Lo Verso. Comparative analysis of simplified daylight glare methods and proposal of a new method based on the cylindrical illuminance. Energy Procedia 78 (2015) 699 – 704, doi: https://doi.org/10.1016/j.egypro.2015.11.074.

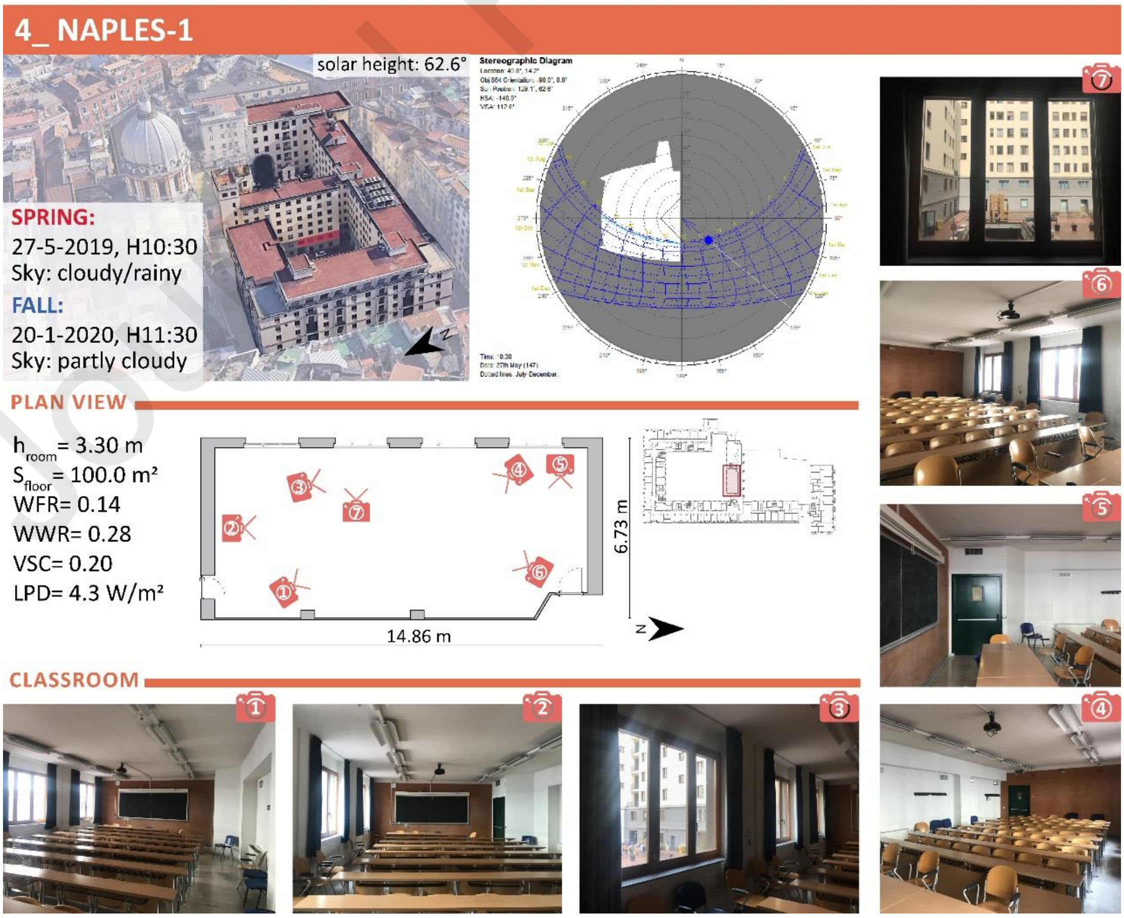
Annex 1a – Description of the eight classrooms used for the DAYKE-Italy project: TUR-1, TUR-2.



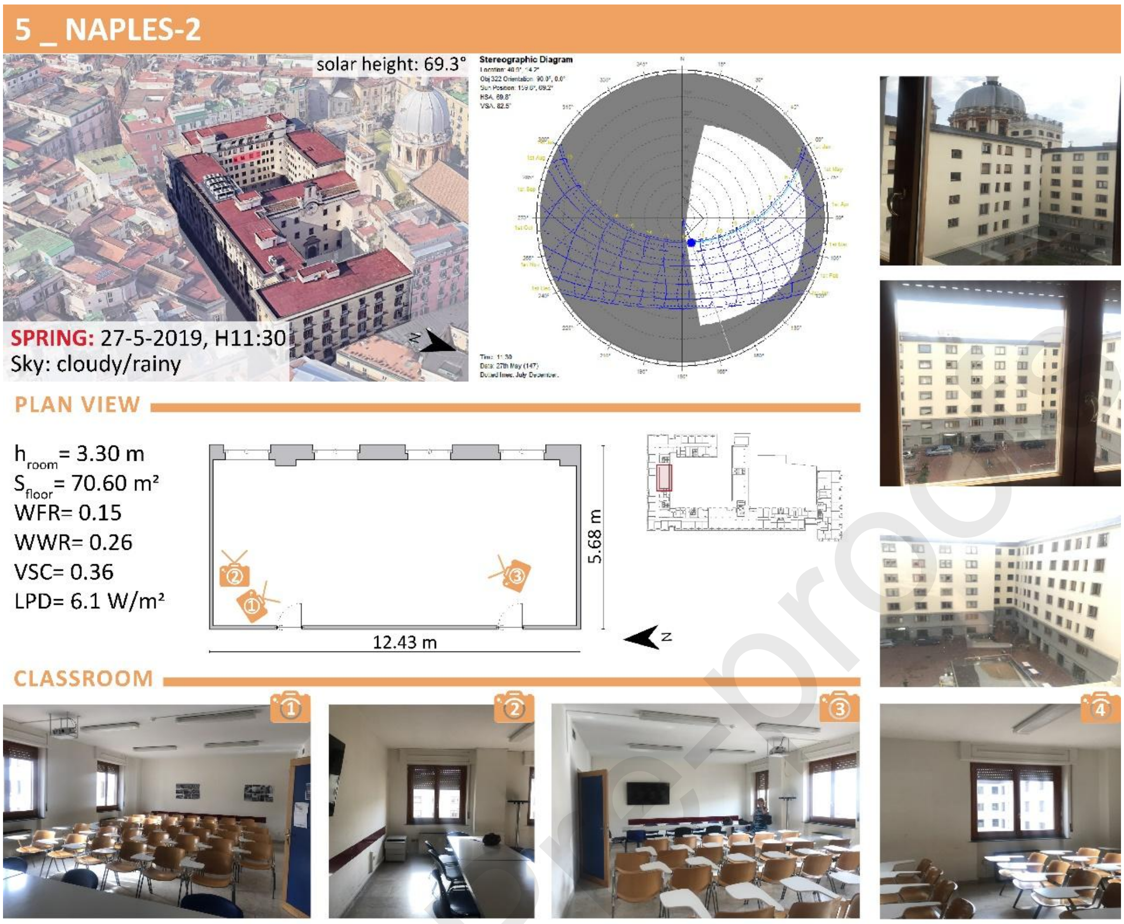


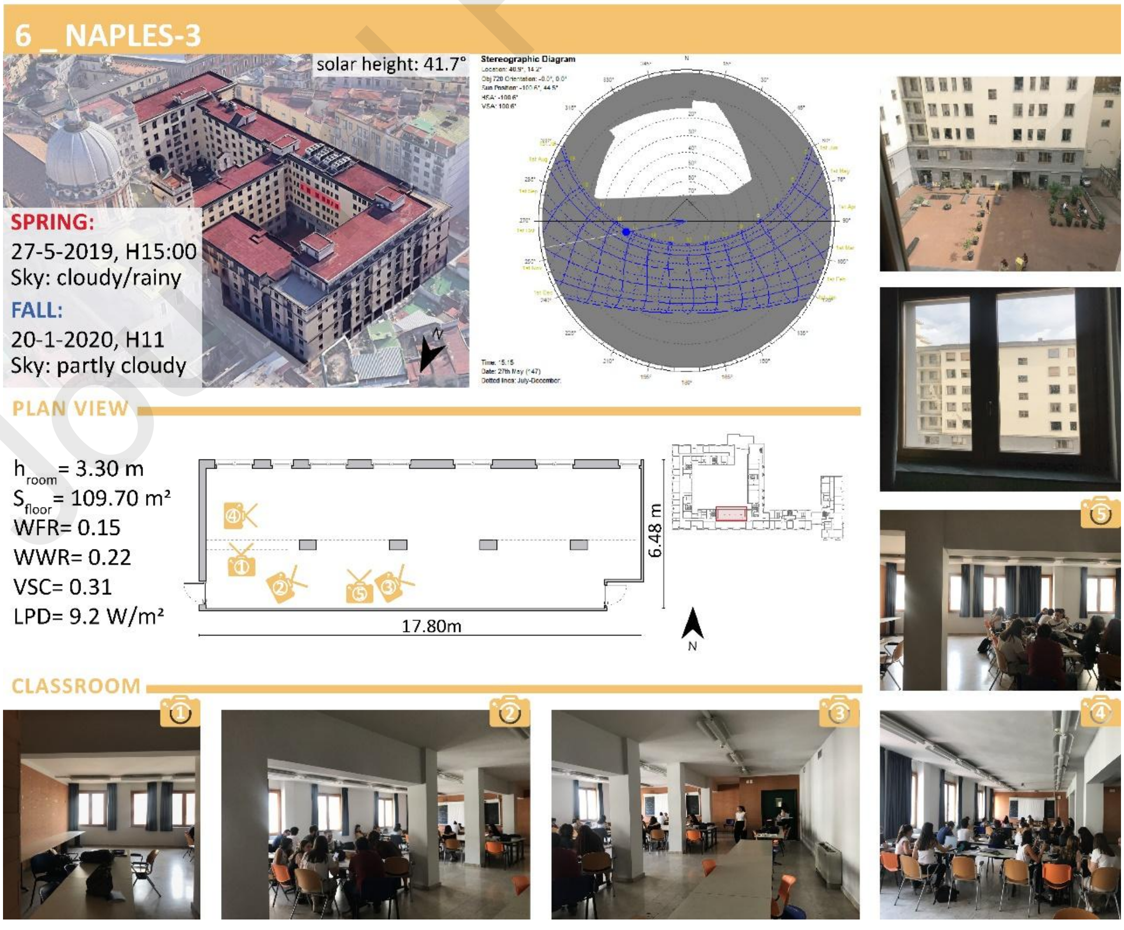
Annex 1b – Description of the eight classrooms used for the DAYKE-Italy project: VEN, NAP-1.



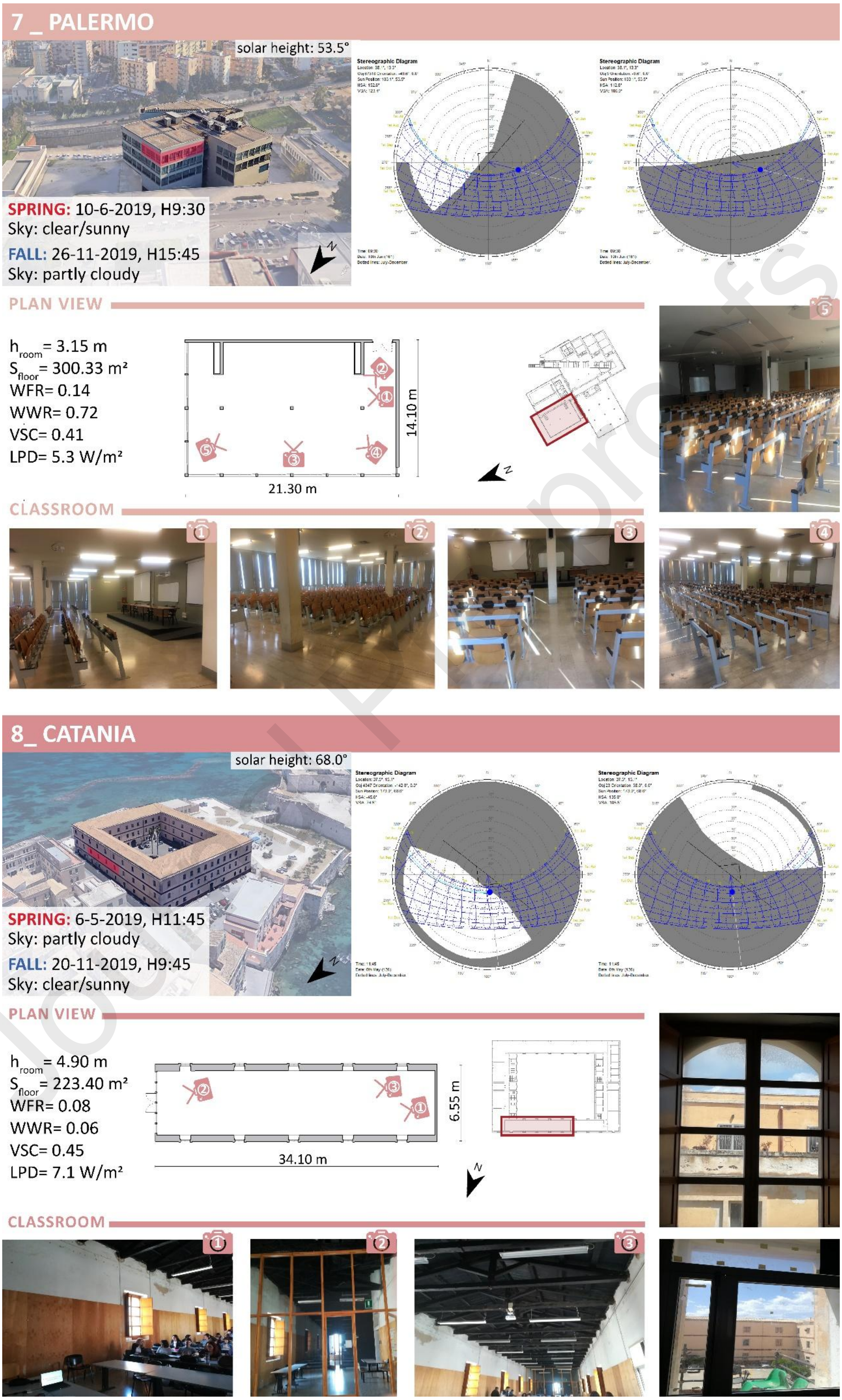


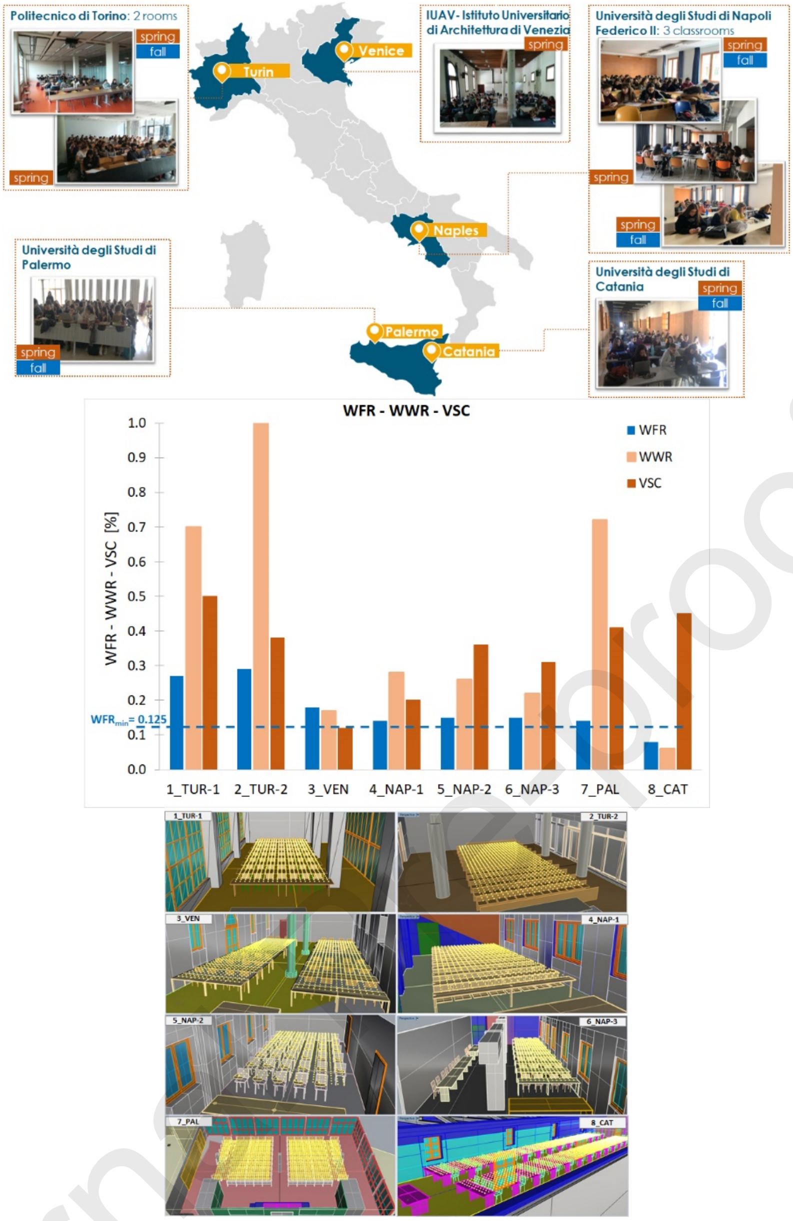
Annex 1c – Description of the eight classrooms used for the DAYKE-Italy project: NAP-2, NAP-3.





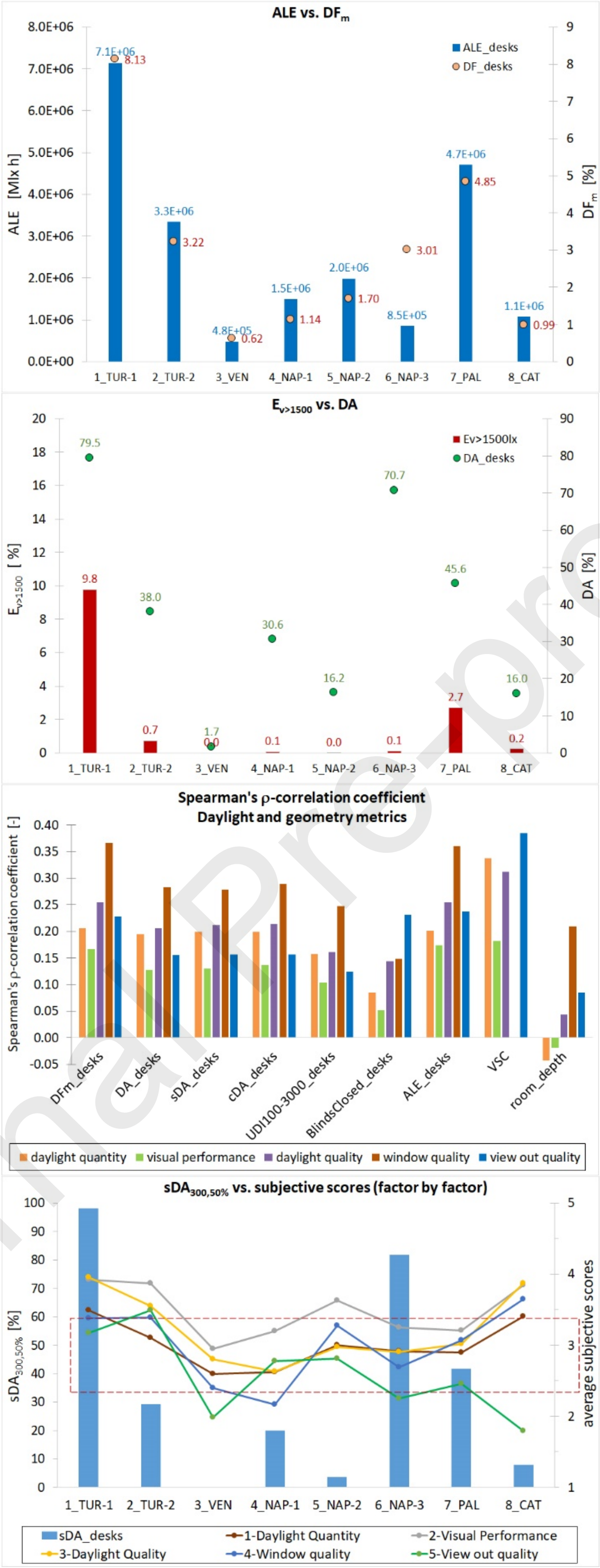
Annex 1d – Description of the eight classrooms used for the DAYKE-Italy project: PAL, CAT.

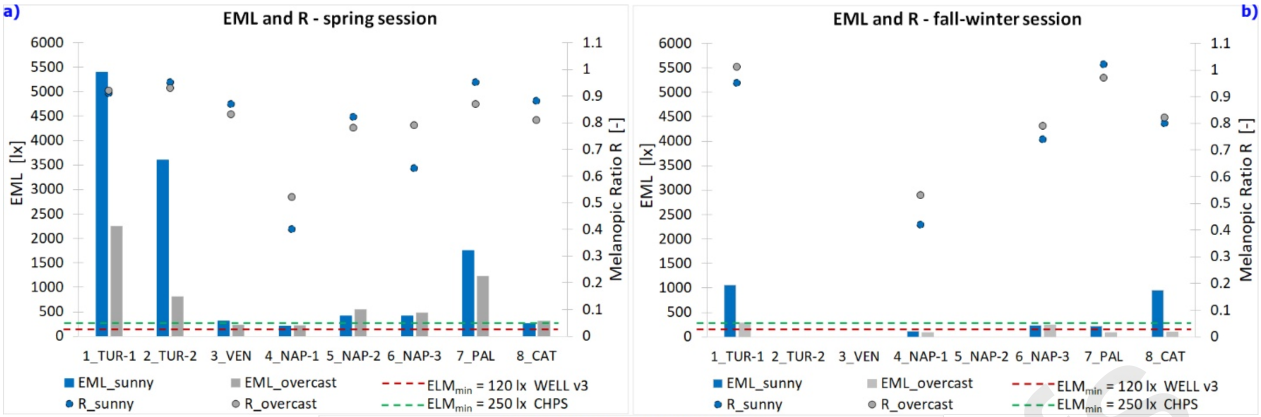


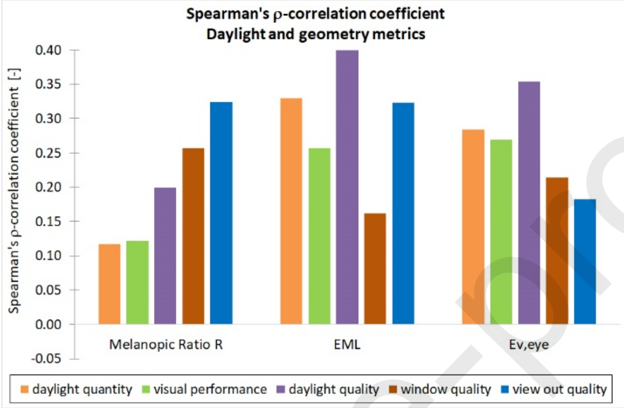


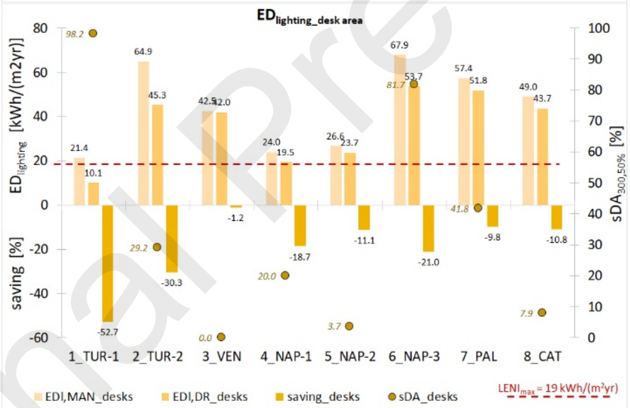
Politecnico di Torino: 2 rooms
spring
fall
spring
Turin
Venice
IUAV- Istituto Universitario di Architettura di Venezia
spring
Università degli Studi di Napoli Federico II: 3 classrooms
spring
fall
spring
spring
fall
Naples
Università degli Studi di Palermo
spring
fall
Palermo
Catania
Università degli Studi di Catania
spring
fall
WFR - WWR - VSC
WFR
WWR
VSC
WFR - WWR - VSC [%]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
WFRmin= 0.125
1_TUR-1
2_TUR-2
3_VEN
4_NAP-1
5_NAP-2
6_NAP-3
7_PAL
8_CAT

a)
DFm
DF [%]
DFm,min = 3% Italian Legislation
DFm,min = 2% Italian CAM
DFm,min = 1.8% EN 17037 (TUR-VEN)
DFm,min = 1.6% EN 17037 (NAP)
DFm,min = 1.5% EN 17037 (PAL-CAT)
8.20 8.13 3.81 3.22 0.66 0.62 1.33 1.14 1.95 1.70 1.36 3.01 5.96 4.85 0.67 0.99
b)
sDF
sDF [%]
sDF(>3%)
sDF(>2%)
sDFmin = 75% LEED ITA
sDFmin = 50% EN 17037
96.3 100.0 100.0 100.0 39.3 67.9 43.7 67.3 0.0 0.0 0.0 0.7 11.4 16.2 7.3 14.4 16.7 32.7 12.3 30.7 13.2 20.7 39.4 63.0 54.7 64.5 69.9 87.1 2.3 5.6 5.6 14.6
c)
DA
DAm [%]
72.7 79.5 32.5 38.0 1.4 1.7 26.6 30.6 16.8 16.2 26.5 70.7 40.5 45.6 10.2 16.0
d)
cDA
cDAm [%]
89.0 91.1 59.8 66.5 18.3 17.6 52.4 56.6 44.8 45.7 53.6 87.0 64.1 74.7 36.1 40.1
e)
sDA300,50%
sDA300,50% [%]
sDA300,50%_min = 75% LEED 3-points
sDA300,50%_min = 55% LEED 2-points
sDA300,50%_min = 40% LEED 1-point
89.1 98.2 26.1 29.2 0.0 0.0 19.7 20.0 7.1 3.7 28.8 81.7 39.4 41.8 7.0 7.9
f)
UDI100-3000
UDI100-3000,m [%]
UDI100-3000_min = 80%
UK School Buidling Programme
89.7 90.7 67.9 78.6 16.6 15.8 58.5 63.5 51.0 53.2 63.3 92.1 67.6 87.1 41.8 46.2
g)
ASE1000,250
ASE250,1000 [%]
ASE1000,250_min = 10% LEED
70.1 93.6 18.5 7.8 0.0 0.0 15.1 10.0 23.7 20.6 0.0 0.0 15.0 3.7 5.1 9.0
h)
% of occupied time with blinds closed
occupied time with blinds closed [%]
69 68 60 56 53 52 25 24 77 76 0 0 81 75 36 46
whole room
desk area
1_TUR-1
2_TUR-2
3_VEN
4_NAP-1
4_NAP-2
4_NAP-3
7_PAL
8_CAT


ALE vs. DFm
ALE [Mlx h]
DFm [%]
ALE_desks
DF_desks
1_TUR-1
2_TUR-2
3_VEN
4_NAP-1
5_NAP-2
6_NAP-3
7_PAL
8_CAT
Ev>1500 vs. DA
Ev>1500 [%]
DA [%]
Ev>1500lx
DA_desks
Spearman's ρ-correlation coefficient
Daylight and geometry metrics
Spearman's ρ-correlation coefficient [-]
DFm_desks
DA_desks
sDA_desks
cDA_desks
UDI100-3000_desks
BlindsClosed_desks
ALE_desks
VSC
room_depth
daylight quantity
visual performance
daylight quality
window quality
view out quality
sDA300,50% vs. subjective scores (factor by factor)
sDA300,50% [%]
average subjective scores
sDA_desks
1-Daylight Quantity
2-Visual Performance
3-Daylight Quality
4-Window quality
5-View out quality


a)
EML and R - spring session
EML [lx]
Melanopic Ratio R [-]
1_TUR-1 2_TUR-2 3_VEN 4_NAP-1 5_NAP-2 6_NAP-3 7_PAL 8_CAT
EML_sunny
EML_overcast
R_sunny
R_overcast
ELMmin = 120 lx WELL v3
ELMmin = 250 lx CHPS
b)
EML and R - fall-winter session
EML [lx]
Melanopic Ratio R [-]
1_TUR-1 2_TUR-2 3_VEN 4_NAP-1 5_NAP-2 6_NAP-3 7_PAL 8_CAT
EML_sunny
EML_overcast
R_sunny
R_overcast
ELMmin = 120 lx WELL v3
ELMmin = 250 lx CHPS


Spearman's ρ-correlation coefficient
Daylight and geometry metrics
Spearman's ρ-correlation coefficient [-]
Melanopic Ratio R
EML
Ev,eye
daylight quantity
visual performance
daylight quality
window quality
view out quality


EDlighting_desk area
EDlighting [kWh/(m2yr)]
saving [%]
sDA300,50% [%]
1_TUR-1 2_TUR-2 3_VEN 4_NAP-1 5_NAP-2 6_NAP-3 7_PAL 8_CAT
EDl,MAN_desks
EDl,DR_desks
saving_desks
sDA_desks
LENImax = 19 kWh/(m²yr)


SUBJECT and GOALS
DAYLIGHT in CLASSROOMS
COMFORT - IEQ
HEALTH
ENERGY SAVING
DAYKE project
DAYKE-Europe
DAYKE-Italy (object of the paper)
RESEARCH QUESTIONS
RQ1: do daylight metrics prescribed in different standards/protocols fit the subjective responses expressed by students?
RQ2: can a classroom noncompliant with daylight metrics/criteria be positively judged by students, and vice versa?
RQ3: do circadian metrics based on EML fit the subjective responses expressed by students?
RQ4: is there a correlation between energy use/saving and some daylight metric/criterion?
CASE-STUDY
5 universities in ITALY
8 classrooms
2 sessions
(spring; fall-winter)
METHOD
QUESTIONNAIRE SURVEY
PERCEPTION
5-point bipolar scale
daylight quantity
daylight pleasantness
visual performance (desk, monitor, blackboard)
windows/shading
view to the outside
542 responses collected
SIMULATIONS
DIVA
ALFA
DAYLIGHT METRICS
DFm - sDF - ALE – DA – cDA -
sDA - ASE – UDI – DGP
ENERGY METRICS
LENI (lighting energy demand)
ΔLENI (savings)
CIRCADIAN METRICS
ELM
melanopic ratio
Ev,eye
STATISTICAL ANALYSES
correlation between subjective responses and objective metrics from simulations
RESULTS and CONCLUSIONS
FACTOR ANALYSIS
5 factors explained 74.94% of the variance of the data
1. daylight quantity
2. visual performance
3. daylight quality
4. windows quality
5. view out quality
RQ4: is there a correlation between energy use/saving\ and some daylight metric/criterion?
• significant correlation for most daylight/circadian metrics
• highest correlation for EML, then for DA, sDA, and cDA
RQ1: do daylight metrics prescribed in different standards/protocols fit the subjective responses expressed by students?
• significant correlation for all daylight metrics
• higher correlation for DFm and ALE, intermediate for DA, cDA, and sDA lower correlation for UDI
• VSC (vertical sky component) show significant correlation)
RQ2: can a classroom noncompliant with daylight metrics/criteria be positively judged by students, and vice versa?
• classrooms with poor daylighting according to objective metrics (f.i. in terms of sDA) are judged with a score around 3 ('acceptable')
• classrooms with the highest daylight performance are judge very similarly to classrooms with poor daylight performance
RQ3: do circadian metrics based on EML fit the subjective responses expressed by students?
• significant correlation for all circadian metrics
• higher correlation for EML (even higher than for daylight metrics), lower for Ev,eye
• higher correlation for metrics based on vertical illuminance than on workplane illuminance