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Natural light optimization in an existing primary school: human centred design and daylight retrofitting solutions for students wellbeing

Carla Balocco[1], Irene Ancillotti[2], and Antonella Trombadore[1,*]

[1] Department of Architecture, via Mattonaia 8, University of Florence, Florence, Italy
[2] Architect at the Studio Sani Ingegneria srl, via Reparata 40, Florence, Italy

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Abstract. How the human centred design solutions will implement the benefit of daylighting in an existing primary school? This paper shows research experiences on students visual comfort inside the school building *Don Milani*, in Prato (Italy). The layout of training spaces, distribution and functional organization is also re-designed as flexible/resilient space/place, with a focus on the control of natural light effects for the luminous environment quality, vision and perception, but also an energy consumption reduction. The project is based on a human centred design approach, fostering the integration between sustainable lighting, human perception and biological clock (i.e. circadian rhythm) connected to the Sun daily path. Results showed the importance of natural light optimization to assure different children activities and behaviour, reorganization of the indoor environment and work/observation stations, combining the light colour variability of different materials. Findings highlighted that natural light quality assessment is fundamental to achieve not only a good lighting quality and energy consumption reduction, but also high level of visual comfort in learning spaces, implementing both the students wellbeing and their proactive behaviour, as it should be in a sustainable school building.

Keywords: Natural lighting / visual and perception quality / sustainable school building / digital means

1 Introduction and background

The research and design area of lighting engineering has considerably expanded, interacting with items of other sciences and disciplines, and it is also constantly developing and evolving. It is a sign of success, but also of acquired complexity. Tackling a lighting project only by modelling and pragmatic point of views, can lead to a solution, meeting the suggested limits and energy consumption reduction, but this raises the question of the misunderstanding concept of "scheme" that can reduce the project to quantity and quality of light control [1–5]. Moreover, the existing, renovated/refurbished buildings and especially the historic ones, do not always meet the standard requirements, often due to their use changed over time.

Natural light is fundamental for visual well-being and health, effectiveness and rational use of energy for any kind of building [1–5]. As a matter of fact, some literature studies have highlighted the importance of control and design the natural light effectiveness for energy consumption reduction and guaranteeing daylight autonomy [5–8]. Some researches [1–15] have provided specific lighting design methods to assure the proper lighting conditions for different uses and activities, especially in school buildings at the proper time and proper area of each classroom, in compliance with the CIE suggestions [15,16]. Some authors by means of several climate based daylight (CBD) simulations, have provided the effective combination between natural and artificial light on spatial daylight autonomy and annual sunlight exposure metrics [17]. In particular, a recent study [1] based on a wide review, has demonstrated the potential and limitation both of different daylighting systems, applied to windows and building façades, and literature metrics to quantify and assure visual comfort and energy efficiency. Other researches have investigated daylight quality and natural light uniform distribution inside different classrooms also for refurbished heritage buildings used as schools [18–20]. The authors with climate-based natural light simulations supported by experimental measurements, have analysed many different daylight retrofit solutions, referring to the useful daylight illuminance index (UDI) [18–20]. They have also suggested optimal solutions of ceiling reflectors and exterior window reflectors integration [18–20]. Literature studies show the importance of controlling natural light in relation to latitude, local climate, building orientation and distribution of its internal environments, different uses and visual

* e-mail: antonella.trombadore@unifi.it

tasks, highlighting the advantages of its maximum use [14,20–22]. It has been demonstrated how the energy sustainability and green integration solutions for buildings, provide specific evaluation criteria and visual comfort indices and the necessary natural light quantity for specific tasks, connected to the visual field of the subject [14, 23].

On the other hand, it is well known that the impact on energy consumption reduction and CO_2 emission limitation, can be achieved by means of maximum and effective use of natural lighting, in workplaces, schools, but also in any cultural heritage building, as long as it is controlled.

It is widely known and attested that the positive effects on people's health, degree of concentration, well-being and quality of life, the subject's biological clock i.e. circadian rhythm, are obtained with a lighting design based on the optimal mixture between natural and the artificial light. In particular, the latter must be designed using LEDs with white tunable, dimmer and DALI system, and IoT connection for a dynamic lighting integration with the behaviour and conscientious sensory response of people [20–22].

Most of literature research has highlighted that any study on light (natural, artificial and their mix) cannot neglect the non-visual effects of light and therefore, the lighting quality assessment and human centric lighting (HCL) concept [5–10]. The latter is referred to the human biological clock synchronization with the solar day natural dynamics (daylighting) with particular attention to the relationships among discomfort glare, physiological effects and visual performance [5,10].

Other studies have investigated lighting and sources design, referring to the circadian light of tunable white technology with dynamic adjusting of spectrum and intensity [4]. They have also suggested a useful methodological approach for smart lighting system design, considering dynamic colour temperature and emission spectrum changes, together with user visual comfort criteria [4]. In particular, other studies on this matter have proposed an advanced smart self-calibrating lighting control system for energy consumption reduction [11].

Some literature has suggested effective factors, specific parameters and metrics (e.g. circadian action factor, circadian stimulus, equivalent melanopic lux) for the light quality assessment and luminous climate description of several studied environments, referring to human physiological, emotional and visual responses to light [3,16]. New indexes and approaches for indoor visual/perception comfort based on corneal illuminance [2,19,20] has been investigated. Research in lighting design with focus on green sustainable and human centric lighting, has evaluated human vision and perception mechanisms in response to different effects of natural and artificial lighting and their optimal controlled combination e.g., glare sensation, colour perception, users' preferences for different luminous conditions [16,19–23].

An impressive literature review [1] has highlighted how starting from the lighting design aimed at the users' vision and perception quality, and taking into account the integration of advanced IoT, wireless technologies and HCL approaches, it is possible to realize a new smart lighting design integrated with virtual reality (VR) [1]. The authors have shown that VR, despite the limitations connected to the real and variable in time and space environment, strong variations in use and lighting conditions (e.g. natural and artificial dynamics), can be an effective lighting design tool, because it allows: (computational and realization/operation) time and cost saving; evaluation of indoor visual and emotional environment perception; control of combined and synergic effects of specific selected variables; assessment of cause-effect relationships; evaluation of day-lit spaces quality; study of people perception and behaviour inside a different dynamic luminous climate, taking into account level of immersion, non-visual effects and human centric lighting [1].

Some authors have investigated the potential of artificial neural networks, as predictive model for buildings energy consumption evaluation [23]. In particular, they have assessed the daylight harvesting combined with different orientations at the ambient level, providing a useful tool for the architecture and lighting design [23].

Few studies have investigated the daylighting improvement in educational buildings, by means of different approaches and evaluations. Some authors have highlighted low daylighting performance and the connected glare and overheating problems in buildings applying the Daylight Factor and the dynamic climatic-based metrics of Daylight Autonomy and Annual Sunlight Exposure [24–31]. Others authors have investigated the different lighting designs, based on the optimal combination between natural and artificial light, to reduce glare and overheating phenomena in educational buildings, also providing a method for energy saving based on automatic lighting control systems [31–34].

The available literature on learning spaces, as indicated in the document prepared by Indire [35], is based on evaluation methods that they can be quantitative, used for example in the American collection, or qualitative, used in surveys conducted for example in Europe and Australia. In the Anglo-Saxon educational sector, the Evidence Based Practice has developed in recent years [36]. Evidence based education, as stated in the text 'What is Evidence Based Education" [37], appears to be a research approach which aims to encourage evidence-based decision-making. Evidence based design (EBD) is currently widely used in the hospital sector, however, in recent years, the evidence-based research method has progressively spread both within the school environment and internationally. Analyzing the data provided by the evidence based regarding the design of educational spaces we find that the brightness, the acoustics, the internal thermo-hygrometric conditions and the air quality, as well as the energy-environmental sustainability of the design solutions are fundamental factors. Thermal comfort and lighting are, in fact, the elements most mentioned by teachers as influential parameters in pupils' learning.

There are also many studies that highlight the concrete correlation between the school results obtained and the learning environment, such as the analysis carried out by Barrett et al. [38].

Starting from the above researches, our present study focused the concept on energy and environmental sustainability, especially with lighting sustainability and quality, cannot neglect sustainable centric human lighting. Since, the current energy situation requires that any building meets the ZEB requirements and the energy transition (all electric) with maximum integration and use of renewables, it would be advisable to consider that the only real renewable energy source is the Sun, in its components, i.e. thermal and luminous. This fact provides direct consequences on thermal and luminous quality of the environment and human responses to light, especially natural light.

Our research and project activities investigate the balance between natural lighting and artificial, exploring the potential and limitation of two suggested different daylighting systems, applied to windows and building façades, compared not only with literature metrics, to quantify and assure visual comfort and energy efficiency, but also with other researches investigating daylight quality and natural light uniform distribution inside different classrooms for refurbished heritage buildings used as schools. The added value of Don Milani experience is combining the lighting design aimed at the users' vision and perception quality, and taking into account the integration of advanced IoT.

A simple methodological approach was proposed. It can be a useful tool for lighting design in the spaces of existing school buildings intended for multifaceted uses and modifiable over time, as the pandemic consequences have imposed, by means of a green energy design of spaces that become places and vice versa. Natural light control and its effective use is analysed and simulated by the Dialux-Evo software, in order to optimise the integration of daylight with advanced LED technology, supported by digital means. The study of the internal luminous climate at the existing conditions, allowed the identification of a creative space for different events through the improvement of natural light penetration, energy saving by reducing the artificial lighting consumption, guaranteeing maximum specific daylight autonomy and quality of vision and perception of users. The new proposals, based on natural light control by digital and architectural technologies integration, showed that a green sustainable design can be realized on the maximum use of natural light. Findings demonstrated that the proposed lighting solutions, based on the integration of natural light with LEDs and digital means, can really increase the attractiveness of the space for children, improve communication, education, training and teaching by means of play and fun with light.

2 Sustainable building design for learning and training spaces

According to Rinaldi and as demonstrated by Močinić and Moscarda [39], spatial perception affects all sensory receptors since every process of knowledge it is dependent on the simultaneous activity of different sensory areas. It must be considered that the surrounding environment does not occur through passive assimilation, rather, through psychological stimuli, activities and impulses. Spatial perception therefore turns out to be the result of a complex elaboration characterized by a phenomenon of bipolarity. As a matter of fact, both the objective features of the space and those subjective of people, who live in it, make a complex dynamic interrelated and synergic system. Considering the importance of subjective sensations, the architectural environment turns out to be an experience full of psychological solicitations. Each subject perceives and modifies the physical space in a different way, since the mental image of the environment is different, influenced by the society, socio-cultural background to which they belong and age, as indicated in by Parricchi [40]. For this reason, the space, thought and designed by the adult, is not always meaningful and corresponding to the needs of the child. It would be important to develop a sustainable school environment that considers, respects and satisfies the physical and psychological needs of child/student, promoting creativity and active training in dedicated environments designed by means of a lighting design in relation to their developmental age thresholds.

3 Method

The quantification of the indoor luminous climate is carried out by the integration between some basic experimental spot measurements and literature evidences, with lighting simulations at dynamic conditions. The existing lighting system and its effects, is assessed with basic checks referred to HCL and sustainable lighting. The main aim is always the evaluation of the maximum possible use of natural light, by means of solar radiation control and a light design in order to produce the optimal combination with the artificial light.

In Italy there is no specific legislation for lighting in schools. For this reason it was necessary to refer mainly to international standards.

The analysis of the natural light quantity and quality in the environment (classroom) is developed applying some fundamental indicators. The indicators used, are: the average daylight factor FLDm (with reference to the National Technical Regulations of 1975 [41]) the daylight autonomy DA, the spatial daylight autonomy sDA (approved by the Illuminating Engineering Society IES LM-83-12 [42]), the useful daylight index UDI, the annual solar exposure ASE, the minimum, average and maximum illuminance Emin, Em and Emax, and the illuminance uniformity U0 and luminance distribution values in compliance with [43].

For the artificial light, the following indicators are considered: unified glare index UGR and luminance uniformity [43]. The lighting simulation for the current condition allow the identification of the criticalities and the definition of the lighting concept proposed. The basic model is validated with some spot measurements, carried out according to limited school access, and comparison with experimental literature evidences [15, 19–21, 33].

Precautionary conditions are considered in reference to the worst days of the year. The latter is identified by means of the analysis of the real climatic data of the last five years,

Fig. 1. The *Don Milani* school building in Prato, near Florence.

provided by the LaMMA-CNR-IBIMET database. This makes it possible to identify the worst days from a climatic point of view due to solar radiation, air temperature and relative humidity, and light in terms of number of sunshine hours and illuminance values on the horizontal plane.

The classroom is the space studied. The new lighting proposals, considering current studies and research findings on the subject, are based on the natural light use and control, for a project that uses light to underline how knowledge is a constructive and social process in continuous dynamic evolution. Therefore, the new lighting for classrooms is designed to provide several flexible spatial configurations, allowing children to adapt and transform the classroom space, developing their creativity enhancing their practical and cognitive attitudes. Artificial light is designed with dimmable and programmable LED systems, for both colour temperature variation and emission spectrum, in compliance with natural light dynamics due to Sun path.

4 The case study and 3D model for digital twin development

An existing primary school in Florence (Italy) is investigated.

The *Don Milani* school building is in Prato, near Florence (Italy) and consists of a basement and three floors above ground. On the North-East side the school borders with residential buildings, on the two West and South sides with agricultural land. The *Don Milani* school building includes the kindergarten, primary school and the first grade secondary school (Fig. 1).

The classroom is a particular environment for any lighting project, due to different teaching tasks, intense and dynamic visual effort and adaptation of the static and dynamic visual field to near horizontal planes and distant vertical planes. Two representative and particularly critic classrooms, from the lighting point of view, are identified. A preliminary study is developed for the knowledge of solar path on the building facades and shadows cast by the surrounding buildings. The first classroom on North-East (hereinafter C1), has critical conditions for the winter and summer periods and the second on South-West (hereinafter C2) mainly for the summer period. C1 has a 43.6 m^2 floor and a 12.4 m^2 glazed surface with a 0.28 aero-lighting ratio. C2 has a 42.9 m^2 floor, 12.5 m^2 glazed surface with 0.29 aero-illumination ratio. The aero-lighting ratio is higher than that one suggested of 0.125 for both classrooms. In particular, in Italy, the check of the proportion between openings and walkable surface (aero-lighting ratio) is the first indicator, albeit large maximum, to obtain the building usability and demonstrate that the levels of safety, hygiene, air healthiness and quality comply with the Italian law provisions [41]. By means of digital building information management technologies (BIM – Building Information Modelling) the 3D virtual model of the school building is realised in order to elaborate an integrated and intelligent digital management tool of both geometric, architectural, distribution and functional data and building performance (Figs. 2a and 2b). The idea is to implement in the future the BIM ad digital twin, combining the building data with a monitoring system (sensor) of indoor comfort. In this way the 3D virtual models of real buildings is capable of dialoguing with the monitoring and control system of energy and environmental data collected continuously, and will be able to highlight critical issues in real time, increasing the level of knowledge and awareness of users, and directing possible behavioural response choices.

5 Lighting at the existing condition

A 3D solid-architectural model of each studied classroom is realized, using Revit software [44] necessary to develop transient lighting simulations by Dialux-Evo software [45].

In particular, the space of the whole floor, where C1 and C2 are located, is also modelled to take into account the shadows and light interaction.

At the existing conditions both classrooms have three rows of lighting fixtures with two luminaires. The manual control system consists of two on / off switches that

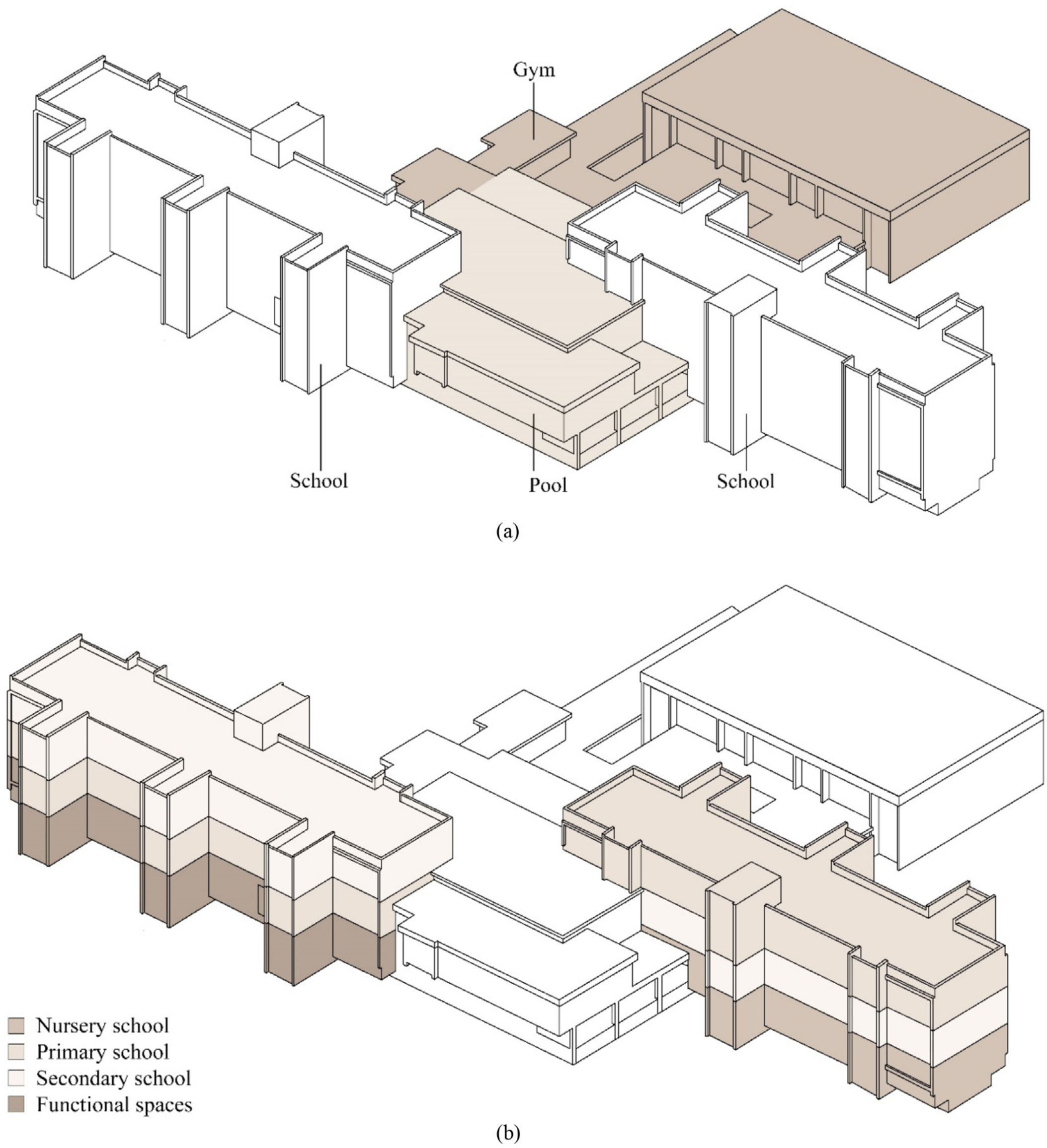

Fig. 2. (a) The BIM model of the whole school building. (b) The BIM model of the primary school building.

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Luminous flux	2042 lm
Yield	78,5%
Connected power	34W
Efficiency	60,1 lm/W

Fig. 3. The lighting fixtures of both classrooms at the exiting condition.

regulate lighting, respectively for the right area and the left area of the environment. The lighting fixtures of both classrooms are shown in Figure 3.

The post-processing of all the data and information, deduced from a detailed photographic survey and comparison with basic literature references [6–9] allows obtaining the different textures, optical, photometric and colorimetric features that have been associated to the various surfaces.

Usually the work surface height varies with respect to the pupils height.

Therefore, considering that children height, between 6 and 10 years old, is a variable height from 107.5 cm to 148 cm for males, and for females from 106.5 cm to 149.5 cm, an average height of 128 cm is considered for all the analyses and simulations.

For C1 and C2, three horizontal reference levels with different heights and one vertical reference plane are used

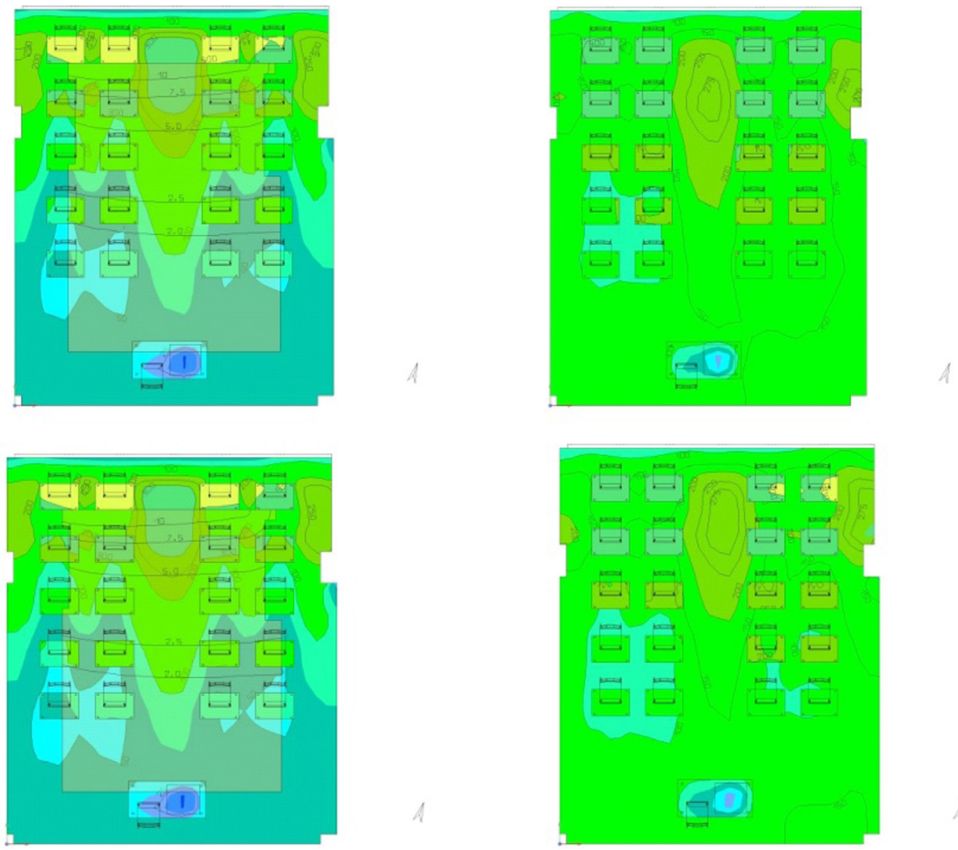

Fig. 4. Existing conditions. Illuminance distribution in C1 due to natural light on 31 January by representation with combination of false colour maps and isolux lines. At the top: illuminance lx with overcast sky conditions and hour 9,00 (left); illuminance lx with overcast sky conditions and hour 16,00 (right). At the bottom: illuminance lx with clear sky conditions and hour 9,00 (left); illuminance lx with clear sky conditions at hour 16,00 (right).

in the simulations: i.e. horizontal plane of the floor, horizontal plane coinciding with the worktops with a height of 0.59 cm from the floor, horizontal plane corresponding to the plane of view of pupils with a height of 120 cm, and finally the vertical plane of the blackboard.

The simulations are developed for the two precautionary days, obtained from the analysis of climatic data, i.e. 31 January 2020 and 12 June 2020, respectively at overcast and clear sky conditions, and for the hours of maximum occupancy.

Simulation results show that C1 is the classroom with the worst light conditions for both the period considered, i.e. January and June.

By way of an example, in Figure 3 are provided the simulation results of the illuminance distribution due to natural light, at the existing state, in C1 for 31 January 2020 with corresponding precautionary sky conditions (overcast and clear sky) and for the two maximum occupancy hours.

The analysis of illuminance distribution due to natural light, shows its non-uniformity and imbalance with evident dark areas compared to areas (especially under windows and on worktops) with the highest illuminance values and highest UGR values compared to the suggested limits (Fig. 4). Analysing the images of Figure 4 it is evident that the environment is rather dark.

As proof of this, the artificial lighting system is always on, during all the hours of occupation especially during winter.

6 New lighting proposals for the dynamic space of the classroom

The analysis of existing state results, suggests new lighting proposals oriented to the maximum and most effective use of natural light with optimal combination with that artificial.

In particular, for the new lighting design, only C1 is investigated because its worst lighting conditions and the most used for teaching and recreational activities. To avoid expensive and invasive interventions, the existing windows are kept, but their frame and conch are coated with matte surfaces. Natural light is controlled and designed for a new functional and distributive reorganization of the space, realized by flexible wooden walls sliding on rails anchored to the ceiling. This dynamic and removable structures for spatial organization is designed for two particular configurations: the first one with amphitheater shape (configuration 1), the second one with “S” shape (configuration 2). Figures 5 and 6a, 6b show the 3D visualization of these two different space/place configurations.

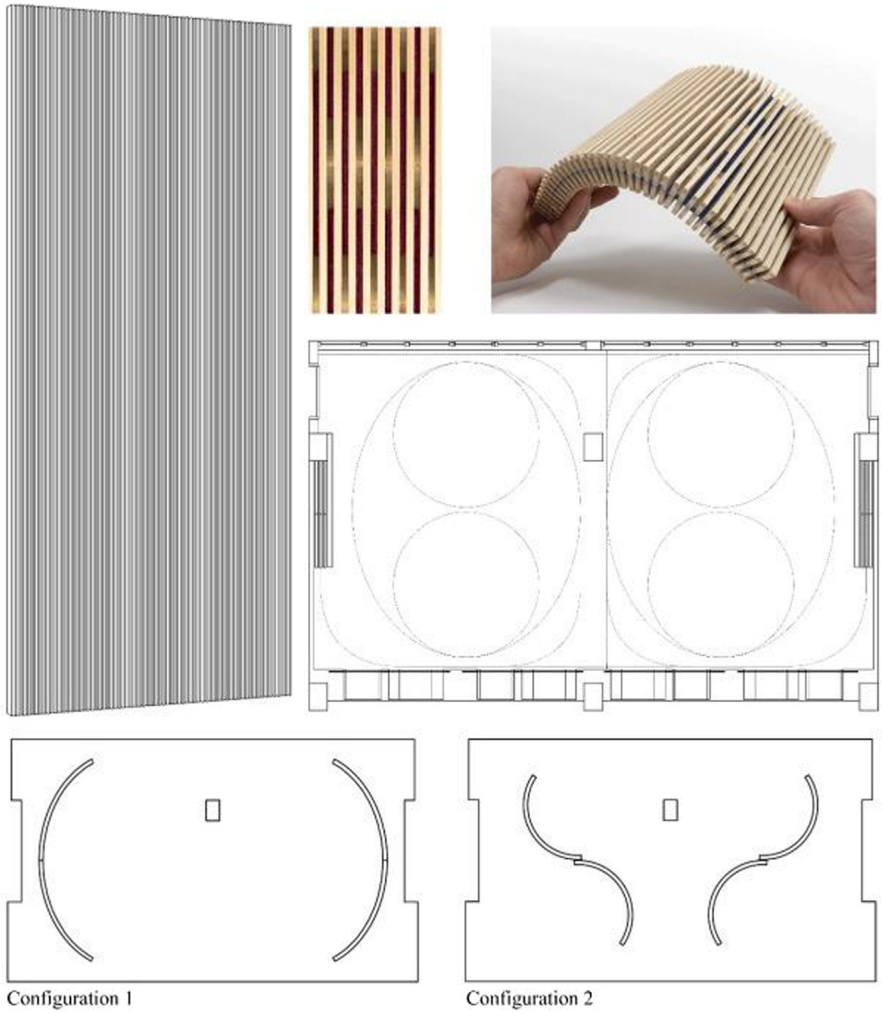

Fig. 5. The functional reorganisation of the classroom space proposed: at the top the flexible wooden wall, and their sliding system on rails anchored to the ceiling; at the bottom the amphitheater shape (configuration 1), and the "S" shape (configuration 2).

In this way, the classroom is a dynamic space and also adaptable to very different children's activities. The matte surfaces and the wooden walls are characterized by colorimetric characteristics and in particular, by reflection, diffusion and glossiness referring to [46–49]

The flexible wooden walls are considered completely removable combined with modular furnishings, easily found on the market.

In particular, dedicated colorimetric references is taken into account, considering current research in the pedagogical and psychological fields that link colour to the development phases, intellectual growth and learning of children [6,7,10,11,15,16,19–21].

A preliminary study is then carried out to verify the effects of all the wooden slats of the movable walls, inside the visual field of children, due to reflection, diffraction and glare. The results show the possibility of treating the wooden surfaces as uniform, but characterized by their own surface roughness and colour.

The optimal combination of natural and artificial light, into the dynamic space, is implemented using two types of LEDs. Consequently, simulations are developed for two lighting proposals (i.e. N1 and N2).

In Figure 7 the photometric characteristics of the LEDs used are shown.

Particular furnishings and their distribution and their optical and colorimetric characteristics, were considered in all the simulations. Reference was always made to the planes of different visual tasks connected to the two lighting configurations.

Implementing digital technologies control, all the simulations were finalized to the correct and effective lighting produced by natural light alone, by that artificial and their optimal combination.

The boundary conditions were imposed referring to the current standards and literature suggestions [6,9,15,16, 41–43] i.e.: 500 lux for dominant visual task in the environment, 400 lux for the average illuminance of the surrounding area, 0.6 for illuminance uniformity, 19 for

Fig. 6. The 3D modelling of the proposed configurations: the amphitheater shape (configuration 1, at the top), and the "S" shape (configuration 2, at the bottom).

Unified Glare Index UGR, hours of use of the classroom equal to 2543 h per year (i.e. precautionary condition of maximum occupancy of 7 h per day for 365 days).

7 Results and discussion

The lighting proposals were designed for vision and perception quality as well as visual well-being strictly connected to the circadian rhythm and therefore, to the biological clock of children.

The integration between natural and artificial light, especially by means of light colour control, showed how the minimally invasive lighting solutions proposed (i.e. N1 and N2) make the environment more natural and more suited to learning development, creativity, play and learning of children, without any glare phenomenon (see Tab. 1).

Both solutions allow dynamic light by means of the luminous flux and colour light variation.

The first solution with LED_1 has a Fresnel lens optic system with maximum zoom and dimmers.

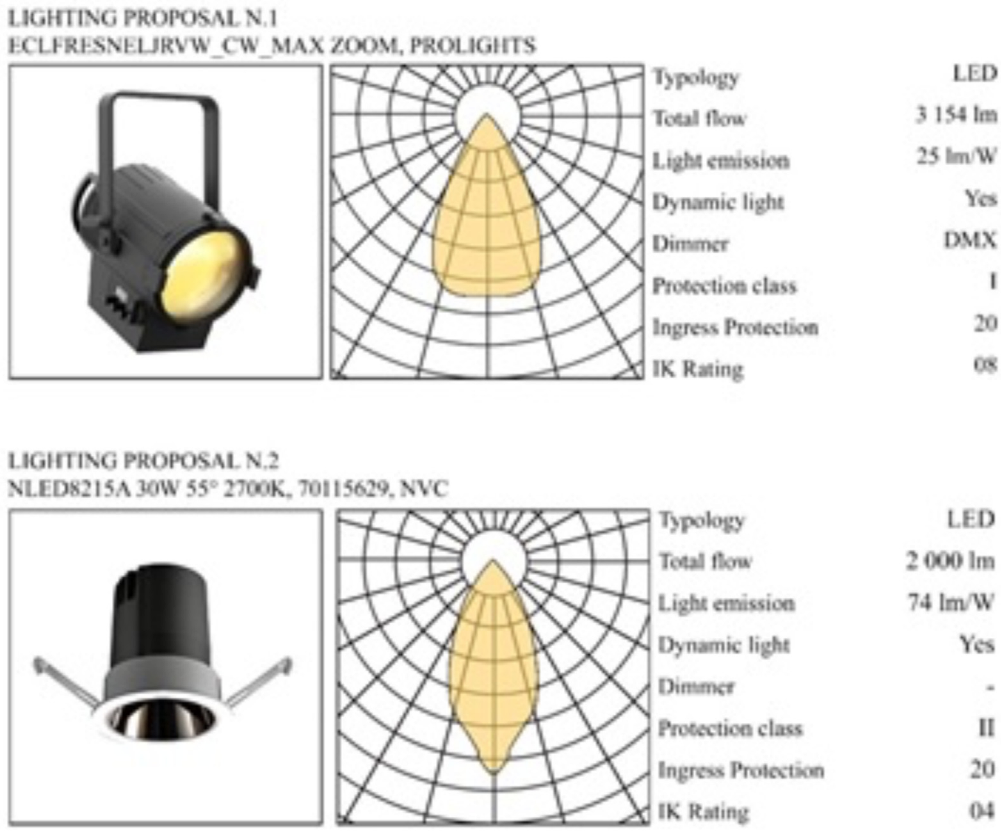

Fig. 7. The photometric characteristics of the two LEDs used, i.e. proposal N1 and proposal N2.

Therefore, despite its luminous efficiency is lower (25 lm/W LED1, compared to 74 lm/W for the second solution with LED2) it is a system that allows a better luminous flux regulation.

As a matter of fact, it is more easily correlated to the intensity, brightness and light colour in the classroom due to natural light, mainly diffused by the matte surfaces and the movable wooden walls, but also to the colour of the perimeter walls, ceiling and floor.

The 5000 K colour temperature of LED1 is the most suitable for environments of this type, both for visual tasks and for optimal lighting conditions. It is also the most suitable for the physical and intellectual characteristics and activities of children.

Furthermore, it offers greater possibilities of variation in colour, intensity, brightness and absorbed power thanks to dimming.

Since there is no appreciable difference between the design proposals which use the two different LEDs (N1 and N2) for each shape of the interior space (corresponding to configuration 1 and 2), the configuration 2, i.e. "S" shape, was chosen, because it allows a dynamic control of natural light, according to the sunlight variation incoming the environment. This can be easily deduced comparing results reported in Tables 1 and 2 and also taking into account the uniformity of luminance as shown in Tables 3 and 4.

The lighting system was designed with DALI connection, varying the pointing and opening flexibility of the light beams for each luminaire. The power absorbed by LED_1 is greater than that of LED2 and then the connected energy consumption, as shown by the LENI calculation results, using the current standard implementation [50].

However, the lighting effectiveness and its quality obtained with LED1 configuration, were undoubtedly higher. The value of the ELI (Ergonomic Lighting Indicator [50]) for the LED1solution was 18 compared to 12 for the LED2 solution. As consequence, the obtained parameters of vitality and visual performance were higher.

It is well know that the ELI indicator allows the evaluation of light quality based on five criteria: A visual performance, B overall appearance, C visual comfort, D vitality, E individuality and flexibility. The ELI indicator was obtained using literature data through sample statistical analyses, which made it possible to reconstruct the values of components A, B, C, D, E.

In Table 2 the results for lighting solution with LED1 and LED2 with configuration 2, are shown in comparison with the existing state: the improvement of the luminous climate in the classroom is clearly appreciable, comparing the values obtained for the lighting energy numeric indicator (LENI), the ergonomic lighting indicator (ELI) and the energy consumption.

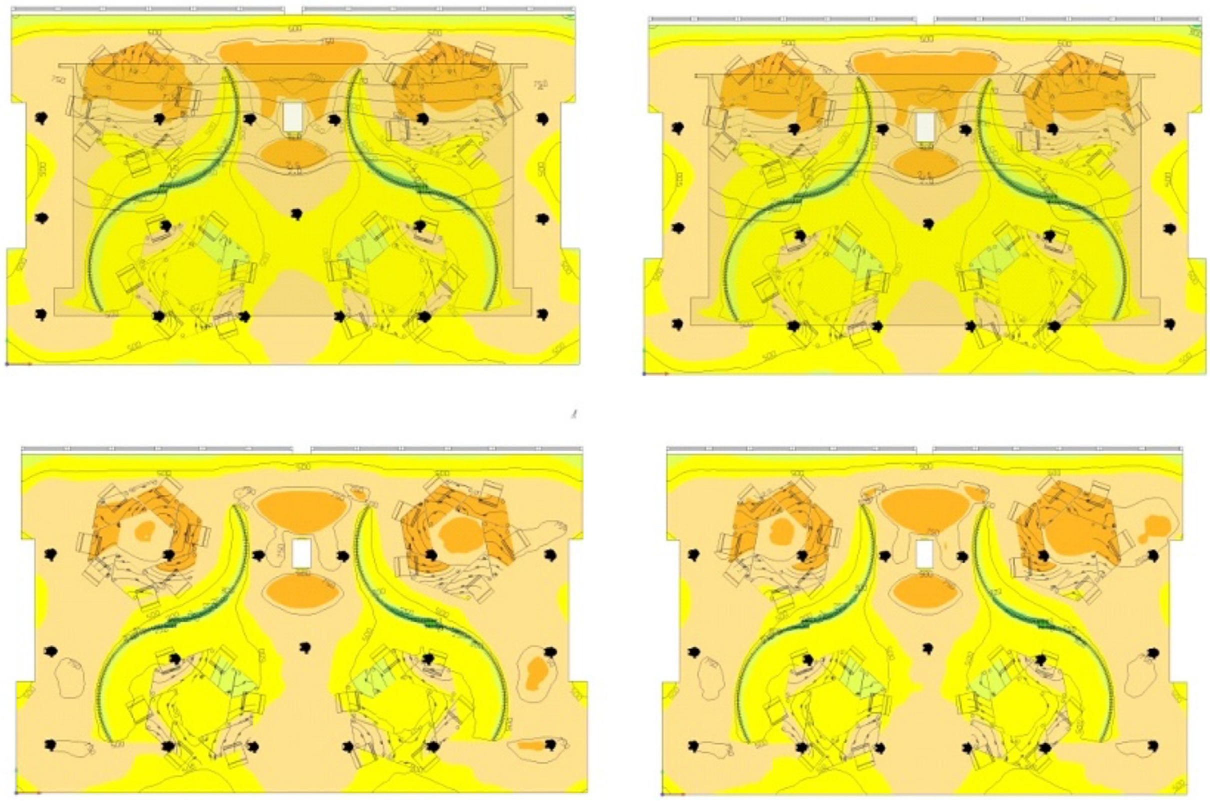

Fig. 8. New lighting design (configuration 2 "S" shape and lighting proposal N1/LED1). Illuminance distribution in C1 due to the mix between natural and artificial light on 31 January, by representation with combination of false colour maps and isolux lines. At the top: illuminance lx with overcast sky conditions and hour 9,00 (left); illuminance lx with overcast sky conditions and hour 16,00 (right). At the bottom: illuminance lx with clear sky conditions and hour 9,00 (left); illuminance lx with clear sky conditions at hour 16,00 (right).

Table 1. The UGR value obtained for the two lighting proposals (LED1 and LED2) and the two different configurations.

	Lighting proposal N.1		Lighting proposal N.2	
	UGR Min	UGR Max	UGR Min	UGR Max
Configuration 1	<10	18,8	<10	15,1
Configuration 2	<10	18,9	<10	16,5

Table 2. The lighting energy numeric indicator (LENI), the ergonomic lighting indicator (ELI) and the energy consumption obtained for Configuration 2 and both the two lighting proposals.

	LENI (kWh/m^2 year)	ELI	Consumption kWh/years
Existing state	28–47	4	2350–3950
Lighting proposal N.1/LED1	27–45	18	2250–3800
Lighting proposal N.2/LED2	10–17	12	830–1400

In particular, it is necessary to consider that both the lighting solutions were simulated under precautionary conditions. This means that all the installed and wired LED1 and LED2 lighting luminaries, were designed to work at full capacity with maximum light intensity for colour temperature of 5000 K and 2000 K respectively. Therefore, if we consider the real operating and regulation conditions of the LED1 by means of the use of dimmers and the DALI system integrated with digital technologies, their greater efficiency and effectiveness is clearly understandable.

In Figure 8 simulation results obtained for the illuminance distribution in C1, with configuration 2 and LED1, on 31 January 2020, at the corresponding precautionary sky conditions (overcast and clear sky) and for the two maximum occupancy hours, are provided.

Table 3. Luminance values at clear sky conditions for the two configurations.

			Lighting proposal N.1	Lighting proposal N.2
Configuration 1	hour 9,00	Min	32,3 cd/m^2	33,8 cd/m^2
		Max	95,4 cd/m^2	99,8 cd/m^2
		Medium	69,7 cd/m^2	77,8 cd/m^2
	hour 16,00	Min	32 cd/m^2	32,7 cd/m^2
		Max	96,5 cd/m^2	99,7 cd/m^2
		Medium	69,1 cd/m^2	77,4 cd/m^2
Configuration 2	hour 9,00	Min	32,7 cd/m^2	40,6 cd/m^2
		Max	96,5 cd/m^2	92,3 cd/m^2
		Medium	69,8 cd/m^2	69 cd/m^2
	hour 16,00	Min	32,6 cd/m^2	39,4 cd/m^2
		Max	96,3 cd/m^2	91,1 cd/m^2
		Medium	69,5 cd/m^2	68,7 cd/m^2

Table 4. Luminance values at cloudy sky conditions for the two configurations.

			Lighting proposal N.1	Lighting proposal N.2
Configuration 1	hour 9,00	Min	30,7 cd/m^2	30,1 cd/m^2
		Max	94,9 cd/m^2	99,6 cd/m^2
		Medium	64,3 cd/m^2	72,3 cd/m^2
	hour 16,00	Min	30,7 cd/m^2	29,3 cd/m^2
		Max	94,1 cd/m^2	99,4 cd/m^2
		Medium	63,9 cd/m^2	71,9 cd/m^2
Configuration 2	hour 9,00	Min	30,7 cd/m^2	35 cd/m^2
		Max	91,4 cd/m^2	80,5 cd/m^2
		Medium	68,4 cd/m^2	63 cd/m^2
	hour 16,00	Min	30,7 cd/m^2	34,7 cd/m^2
		Max	90,6 cd/m^2	80,6 cd/m^2
		Medium	68,1 cd/m^2	63,1 cd/m^2

Moreover, the new lighting design for C1 with configuration 2 with LED1 can guarantee the solar path tracking (natural light control) as the specific time of day and its related emission spectrum variation, following the children' biological clock, but also the best matching of the colour of the light to the colour of the different surfaces. As a matter of fact, in Figure 7 the rendering obtained for all the different work-planes is provided. In particular, Figure 8 shows the rendering obtained by transient simulations of the optimal combination between natural and LEDs lighting for configuration 2 with LED1, with a view at the level of the worktops and seats (tables/desks and children's chairs). That shows the optimal combination of natural light and that dynamic artificial that reproduces its trend, by means of the correspondence between light colour and surfaces/objects/furnishings colour, during the winter period.

The new lighting design produces important consequences on the vision and perception quality, but also lighting quality and sustainability with visual comfort both in winter and summer period at the C1 (Fig. 9).

8 Conclusions: open challenges and future vision

The present research investigated, by means of a systemic qualitative and quantitative method, the optimization of natural lighting performance and visual comfort in typical classrooms of an existing educational building in Italy. All the research findings can be applied, with the modifications and adaptations necessary for each individual case, to the educational architecture in different zones of Mediterranean area with similar climatic characteristics and building/classroom typologies.

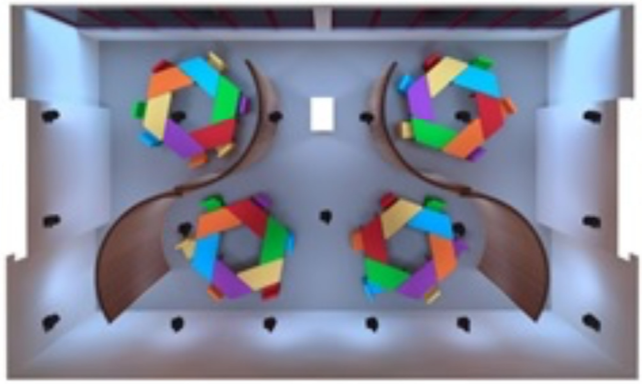

Fig. 9. New lighting design – top view: configuration 2 "S" shape and lighting proposal N1/LED1, with the best mix between natural and artificial light during winter.

Fig. 10. New lighting design – perspective view: configuration 2 "S" shape and lighting proposal N1/LED1, with the best mix between natural and artificial light during winter (at the top) and summer (at the bottom).

Natural light and artificial light source were combined for the proposed lighting solutions. When the outdoor solar radiation and luminance are the highest, the natural light control was designed to replace and integrate, if necessary, the LED white tunable lighting. When solar radiation and natural light are reduced, the LED lighting system, combined with DALI, was used to maintain high lighting quality levels, to reduce lighting contrast and bright visible light, connected to glare phenomena, in the children field of view. Therefore, the LEDs working conditions can be limited to few time a day.

Circadian lighting was the basis of the new light solutions for the classroom studied.

In particular, the combination of DALI technology with drivers tunable white, made it possible to activate the Melanopic Equivalent Daylight Illuminance. Our investigation findings showed that a lighting project for the school environment, needs to maximize natural light use and its control, combined with full spectrum artificial light. This provides considerable reduction of mental fatigue and hyperactivity in children, as proved by recent literature researches [7,11,15].

Our methodological approach showed how any lighting project, based on the integration of natural and artificial light, should be based on the use of digital technologies, DALI wireless, tunable white drivers, widely available today, to provide light quality and vision/perception quality [1,4,23,24].

These integrated solutions not only produce people visual comfort and global well-being but, at the same time, important energy consumption reduction, with consequent positive effects on the environment. This fact becomes even more important if the lighting project is designed for an elementary school, as it acts on learning, attention, perception of space and influences the psychological well-being and physical health of children.

In addition, this study can serve as an example for public administrations, of which most schools in Italy are heritage and property.

The future challenge is based on the application of current digital modelling technologies connected to IOT technologies, but also and above all provides for a more direct and active involvement of the user. This allows the use of technological tool as a means and stimulus to the system to induce it, thanks to communication strategies, to transform the space in which it finds itself by finding solutions, testing on the digital model capable of providing preliminary projections even at a high level, to apply them to the physical model.

The idea of being able to make end-users (teachers and students) active makes it possible to trigger virtuous behaviours by acting on the user's awareness and choice phases. Keeping the project open and involving users in the use phase can generate unprecedented solutions in the indoor space to improve environmental/visual comfort, but also children's learning and responsiveness.

This approach appears particularly interesting in schools' buildings, as places of innovative experience. The engagement process aims to create an experience-based learning framework: the interaction with a flexible and configurable physical space helps to satisfy the different educational needs, promoting the generation of creative solutions.

Declaration of competing interest

The authors declare no conflict of interest.

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Author contribution statement

All the authors contributed equally.

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