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Room and window geometry influence for daylight harvesting maximization – Effects on energy savings in an academic classroom

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Abstract

Lighting systems have a fundamental role for the overall buildings energy consumption. Therefore, remarkable efforts are required for optimizing the lighting systems energy use and for finding new daylight harvesting solutions. In this paper, the impacts on daylight harvesting provided by different room and window geometries and their effects on energy savings are presented. An academic classroom with only one window is chosen as case study and it is supposed that the window orientation is modified according to the four cardinal points. A climate-based approach was chosen for the multiple simulations, carried out via DIVA software, by assuming: square and rectangular classroom geometries with the same total area; square and rectangular window shapes having Window to Floor Ratios (WFRs) equal to 8% and 12%; two different dimmable lighting systems, in order to quantify the energy savings, by considering fluorescent and LED dimmable lamps. The daylight analysis, performed by evaluating both the Daylight Factor (DF) and the Daylight Autonomy (DA), showed that room and window geometries have high influence on daylight harvesting maximization, allowing remarkable energy savings (up to 48.5%) with respect to non-dimmable lighting system. In particular, the best energy result, equal to 467.5 kWh/yr, was obtained with rectangular room and window geometries coupled with LED lamps and WFR equal to 12%.

Keywords: daylight harvesting; energy savings; lighting control; energy efficiency; simulation.

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1. Introduction

The improvement of buildings energy performance is strongly linked to the design choices, during which the optimal building orientation is defined as well as the appropriate windows sizes, that represent one of the most important building components for their influence on energy and comfort results [1]. If accurately designed, the windows allow to maximize the daylight harvesting reducing the lighting systems energy impacts, nowadays responsible of about 20% of the total energy consumption [2]. The research of daylight harvesting maximization and its effects on the buildings energy performance is widely treated in numerous works. The work proposed by Gioia [3] deals with the search for the optimal window-to-wall-ratio (WWR) in different European climates for an office building by considering each of the main orientations. The results showed that the best ideal values can be found in a relatively narrow range ($0.30 < WWR < 0.45$) and that, if worst WWR configuration is adopted, the total energy consumption increases in the range 5-25% with respect to the optimal WWR. Mangkuto et al. [1] investigated the influence of WWR, wall reflectance, and window orientation on various daylight metrics and lighting energy demand in simple buildings located in the tropical climate via simulation study, and they found that the best solution is provided by the combination of WWR 30%, wall reflectance 0.8, and south orientation. In the work presented by Acosta et al. [4] a quantification of daylight factors for different models of windows was conducted with a total of 28 simulations. The obtained results showed that square windows produce daylight factors higher than those measured with horizontal and vertical windows.

Further interesting aspects to be considered for the daylight harvesting maximization are related to the lighting control systems that, according to Doulos et al. [5] represent a complex matter. In their work, they estimate energy savings among LED and fluorescent lamps, and the results highlighted that the optimum choice of the dimmable lamp is required in early stage of lighting design, both for LED and fluorescent lamps. Fantozzi et al. [6, 7] proved that the conversion of existing lighting systems with LED systems combined with appropriate control strategies (which also take into account the contribution of daylight) can allow significant energy savings, over 50%, also in the case of historic buildings and buildings intended to sports. In the work authored by de Rubeis et al. [8], an innovative lighting control system based on natural light monitoring and occupancy control was presented. The results showed that the installation of the proposed system for an academic classroom allows energy savings up to 69.6% and 30.5% of CO_2 emissions avoided.

In this paper, the influence of room and window geometries on daylight harvesting maximization for an academic classroom is presented with a climate-based approach. The main goals of this work are:

- to evaluate the daylight harvesting by considering different room and window geometries and different orientation of the window, and to identify the best solution;
- to determine the energy savings achievable through the different solutions considered;
- to highlight how a climate-based lighting simulation provides a proper early stage of lighting design, in order to maximize the daylight harvesting.

2. Methodology

The methodology employed in this work is based on the hypothesis of different design solutions, that consider different room and window geometries, different window orientation, and two different dimmable lighting systems with fluorescent and LED dimmable lamps. The 3D modeling was carried out through Rhinoceros 3D Nurbs modeling program, while the lighting simulations were realized with DIVA software.

The methodology employed is summarized in Fig. 1.

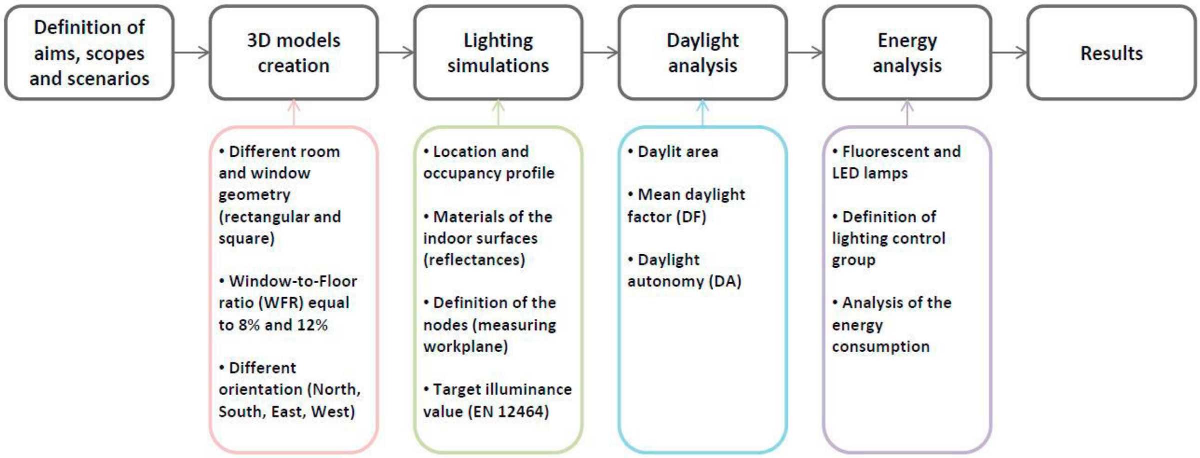


Fig. 1. Methodology flowchart.

2.1. Models characterization

The analysis proposed in this work was carried out by assuming an academic classroom of the University of L'Aquila (latitude 42°21', longitude 13°24'), as a case study. Two different geometries, square and rectangular, each with the same area, equal to 64 m^2, and 3 m height, are hypothesized for the room, object of analysis. The dimension of the classroom represents an average value of classroom of the Faculty of Engineering of the University of L'Aquila. In the model, the following reflectances were set: ceiling (70%), walls (50%), floor (20%). A further hypothesis is that the classroom has only one window, whose shapes were supposed square and rectangular, with Window-to-Floor ratios (WFRs) equal to 8% and 12%. The window has always been positioned in the center of the façade. Moreover, different window orientation was assumed by considering each of the main orientations. The main geometric properties are reported in Table 1.

Table 1. Geometric properties.

Classroom geometry			
Typology	Length [m]	Width [m]	Height [m]
Rectangular	10.7	6.0	3.0
Square	8.0	8.0	3.0
Window geometry			
Typology	WFR [%]	Width [m]	Height [m]
Rectangular	8	3.20	1.60
Rectangular	12	3.92	1.96
Square	8	2.26	2.26
Square	12	2.77	2.77

On the basis of all the possible options, 32 and 64 cases have been analyzed respectively for daylight and energy analyses, since two different lighting systems have been considered (fluorescent and LED lamps). To easily identify the considered cases, an alphanumeric coding has been defined, such as for example XX_FLUO_S_R_8%_N, where: the first code indicates the identification scenario, the second the type of lamp (fluorescent or LED), the third the room geometry (square or rectangular), the fourth the window geometry (square or rectangular), the fifth the WFR (8% or 12%) and the sixth the orientation (north, south, east , west). Fig. 2 shows the 3D models of all the considered cases.

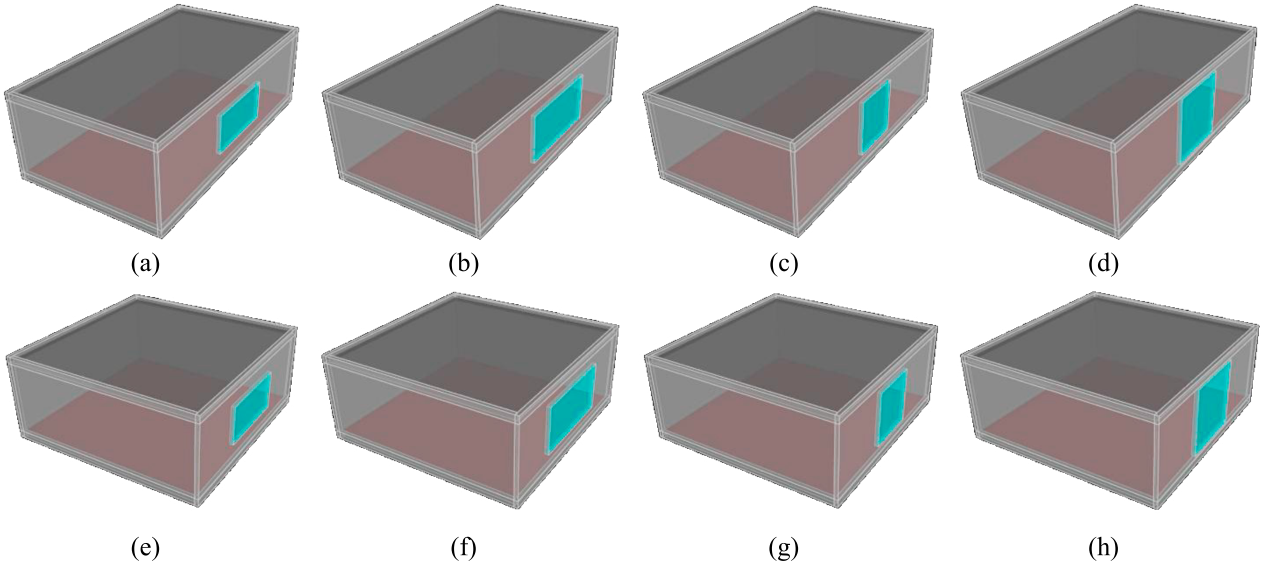


Fig. 2. 3D models. (a) Rectangular classroom-rectangular window-WFR 8%. (b) Rectangular classroom-rectangular window-WFR 12%. (c) Rectangular classroom-square window-WFR 8%. (d) Rectangular classroom-square window-WFR 12%. (e) Square classroom-rectangular window-WFR 8%. (f) Square classroom-rectangular window-WFR 12%. (g) Square classroom-square window-WFR 8%. (h) Square classroom-square window-WFR 12%.

2.2. Climate-based simulation

The lighting simulation were performed with a climate-based approach by using DIVA simulation software, an environmental analysis plugin for the Rhinoceros 3D Nurbs modeling program, that performs a daylight analysis on an existing architectural model via integration with Radiance and Daysim. The weather file for L'Aquila was specifically created [9]. Based on the 3D models, specific nodes on the grid were defined, as workplane sensors, according to the standard EN 12464-1 [10]; the measuring workplane was positioned 0.75 m far from the floor (suggested value by the standard for academic classroom) with a center-to-center equal to 0.44 m. The target illuminance value for an academic classroom equal to 500 lux was selected and a specific annual hourly occupancy profile was created, in order to simulate a typical academic classroom profile, as summarized in Table 2.

Table 2. Annual hourly occupancy profile.

Period [day/month]	Schedule
From 01/01 to 07/01	Unoccupied
From 08/01 to 18/02	From 8.00 am to 1.00 pm
From 19/02 to 12/06	From 8.00 am to 8.00 pm
From 13/06 to 27/07	From 8.00 am to 1.00 pm
From 28/07 to 02/09	Unoccupied
From 03/09 to 21/12	From 8.00 am to 8.00 pm
From 22/12 to 31/12	Unoccupied

The lighting control system was based on manual switch On/Off with photosensors controlled dimming and the daylight analysis was performed by considering both Daylight Factor (DF) and Daylight Autonomy (DA).

From the energy point of view, two different lamps were considered: fluorescent and LED lamps. The main reference parameters for educational buildings, for which the standard EN 12464-1 [10] provides specific requirements, are:

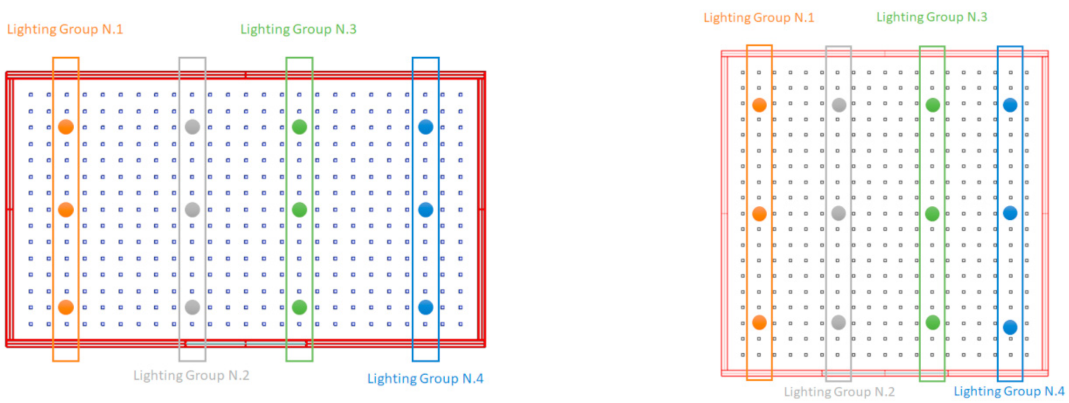
- Average maintained illuminance: Em = 500 lx;
- Uniformity on working plane: U > 0.6;
- Unified glare rating: UGR < 19;
- Color rendering index: CRI > 80.

Characteristics of fluorescent and LED lamps are reported in Table 3.

Table 3. Technical specification of fluorescent and LED lamps.

Physical quantity	Fluorescent	LED
	Glamox C20-S3	Cooper-Eaton PRM123454KZ
Luminous flux [lm]	4534.4	4529.0
Luminous efficacy [lm/W]	75.6	102.9
Power [W]	60	44
Colour rendering index	> 80	> 80
Mounting	For surface mounting	For surface mounting

For all the considered cases, the lighting system design involves the installation of 12 luminaires, positioned as shown in Fig. 3. By assuming to divide the luminaires into 4 groups, 12 photosensors are installed (arranged by columns) for the dimming control.



(a) (b)

Fig. 3. Luminaires and photosensors positioning. (a) Rectangular classroom. (b) Square classroom.

A summary of the main lighting systems characteristics is shown in Table 4.

Table 4. Properties of the designed lighting systems.

Physical quantity	Fluorescent		LED	
	Rectangular classroom	Square classroom	Rectangular classroom	Square classroom
Number of luminaires	12	12	12	12
Total power [W]	720	720	528	528
Mean illuminance [lx]	667	682	647	657
Uniformity	0.72	0.66	0.89	0.85
UGR	18.3	18.4	18.3	18.6

N.B.: the lighting systems design was carried out through ReluxPro software.

3. Results

The main goal of this climate-based daylight analysis is to understand the actual daylight contribution that a room can benefit during a whole year. The analysis was carried out by comparing two different ratios: the Daylight Factor (DF) and the Daylight Autonomy (DA) [11]. The results obtained for the 32 hypothesized combinations are presented in Table 5.

Table 5. Daylight analysis results.

Rectangular classroom			Square classroom		
Case	Mean DF [%]	DA[a] [%]	Case	Mean DF [%]	DA[a] [%]
1_R_R_8%_E	1.6	24	17_S_R_8%_E	1.6	23
2_R_R_8%_N	1.6	19	18_S_R_8%_N	1.6	19
3_R_R_8%_W	1.6	26	19_S_R_8%_W	1.6	26
4_R_R_8%_S	1.6	30	20_S_R_8%_S	1.6	29
5_R_R_12%_E	2.3	34	21_S_R_12%_E	2.3	32
6_R_R_12%_N	2.3	28	22_S_R_12%_N	2.3	27
7_R_R_12%_W	2.3	37	23_S_R_12%_W	2.3	36
8_R_R_12%_S	**2.3**	**41**	**24_S_R_12%_S**	**2.3**	**39**
9_R_S_8%_E	1.4	22	25_S_S_8%_E	1.4	21
10_R_S_8%_N	1.4	18	26_S_S_8%_N	1.4	17
11_R_S_8%_W	1.4	24	27_S_S_8%_W	1.4	24
12_R_S_8%_S	1.4	28	28_S_S_8%_S	1.4	28
13_R_S_12%_E	2.0	32	29_S_S_12%_E	2.0	30
14_R_S_12%_N	2.0	26	30_S_S_12%_N	2.0	25
15_R_S_12%_W	2.0	34	31_S_S_12%_W	2.0	34
16_R_S_12%_S	**2.0**	**39**	**32_S_S_12%_S**	**2.0**	**38**

[a] percentage of the year in which the illuminance values are > 500 lx by daylit alone.

N.B.: best cases are in bold.

It is worth noting that the mean DFs are independent of the window orientation variations, while the DA values change and, in particular, the best values are obtained with a south-oriented window configuration. This predictable result highlights that the mean DF is a less usable ratio for climate-based analyses, for which the DA is more applicable. Indeed, similar results can be found in literature, as for example discussed by Bian and Ma in [12]. Moreover, by analyzing the different room geometries, once orientation and WFRs were fixed, the DA values did not show particular differences between rectangular and square shapes.

The energy analysis, performed through 64 simulations, has allowed to obtain the yearly energy consumption data, by considering all the possible configurations and the different lighting systems adopted (fluorescent and LED lamps). The energy analysis results are summarized in Table 6.

Table 6. Energy analysis results.

Rectangular classroom				Square classroom			
Fluorescent		LED		Fluorescent		LED	
Case	Energy consum. [kWh/yr]	Case	Energy consum. [kWh/yr]	Case	Energy consum. [kWh/yr]	Case	Energy consum. [kWh/yr]
1_R_R_8%_E	914.1	17_R_R_8%_E	672.0	33_S_R_8%_E	981.0	49_S_R_8%_E	722.5
2_R_R_8%_N	1044.3	18_R_R_8%_N	767.6	34_S_R_8%_N	1073.5	50_S_R_8%_N	789.1
3_R_R_8%_W	934.7	19_R_R_8%_W	687.3	35_S_R_8%_W	989.4	51_S_R_8%_W	727.4
4_R_R_8%_S	880.8	20_R_R_8%_S	647.7	36_S_R_8%_S	943.5	52_S_R_8%_S	693.7
5_R_R_12%_E	685.5	21_R_R_12%_E	504.1	37_S_R_12%_E	736.1	53_S_R_12%_E	541.1
6_R_R_12%_N	786.8	22_R_R_12%_N	578.4	38_S_R_12%_N	967.6	54_S_R_12%_N	711.4
7_R_R_12%_W	735.1	23_R_R_12%_W	540.6	39_S_R_12%_W	853.1	55_S_R_12%_W	627.4
8_R_R_12%_S	**635.6**	**24_R_R_12%_S**	**467.5**	**40_S_R_12%_S**	**698.8**	**56_S_R_12%_S**	**513.9**
9_R_S_8%_E	903.3	25_R_S_8%_E	663.6	41_S_S_8%_E	906.8	57_S_S_8%_E	666.6
10_R_S_8%_N	1015.4	26_R_S_8%_N	746.4	42_S_S_8%_N	1081.9	58_S_S_8%_N	795.3
11_R_S_8%_W	1000.1	27_R_S_8%_W	735.2	43_S_S_8%_W	1031.6	59_S_S_8%_W	758.5
12_R_S_8%_S	854.8	28_R_S_8%_S	635.2	44_S_S_8%_S	907.8	60_S_S_8%_S	667.5
13_R_S_12%_E	794.4	29_R_S_12%_E	584.0	45_S_S_12%_E	747.2	61_S_S_12%_E	549.3
14_R_S_12%_N	825.5	30_R_S_12%_N	606.9	46_S_S_12%_N	897.9	62_S_S_12%_N	660.1
15_R_S_12%_W	805.8	31_R_S_12%_W	595.5	47_S_S_12%_W	807.7	63_S_S_12%_W	593.9
16_R_S_12%_S	**728.0**	**32_R_S_12%_S**	**535.3**	**48_S_S_12%_S**	**682.8**	**64_S_S_12%_S**	**502.3**

N.B.: best cases are in bold.

For the rectangular classroom, the best energy scenario is achieved with rectangular window (at the same WFRs), both with fluorescent and LED lamps (cases 8 and 24 in Table 6). Analogously, a square shape of the window provides the best energy results with a square geometry of the classroom (cases 48 and 64 in Table 6). LED lamps always provide energy benefits about equal to 26.4% with respect to fluorescent lamps. Furthermore, although the DA ratio showed that western orientation of the window is always better than the east-oriented condition (see Table 5), the energy results show an opposite trend. Among all the cases, the rectangular classroom coupled with rectangular south-oriented window, WFR equal to 12% and LED lamps is the best case (case 24 in Table 6), with a yearly energy consumption equal to 467.5 kWh/yr. Keeping geometry and orientation fixed, the WFR variation (from 8% to 12%) determines interesting energy saving that, for the best case, is quantifiable in 180.2 kWh/yr (between cases 20 and 24 of Table 6). By comparing lighting systems with daylight control (considered in this work) and the same systems without control, energy savings up to 48.5% are achievable. Selecting the best cases of Table 6, the results obtained are summarized in Table 7.

Table 7. Comparison between lighting systems energy consumption with and without daylight control.

Fluorescent				LED			
	Daylight Control				Daylight Control		
Case	No	Yes	Variation	Case	No	Yes	Variation
8_R_R_12%_S	1234.2	635.6	-48.5%	24_R_R_12%_S	905.1	467.5	-48.3%
16_R_S_12%_S	1328.7	728.0	-45.2%	32_R_S_12%_S	1014.0	535.3	-47.2%
40_S_R_12%_S	1133.6	698.8	-38.3%	56_S_R_12%_S	831.4	831.4	-38.2%
48_S_S_12%_S	1146.0	682.8	-40.4%	64_S_S_12%_S	840.4	840.4	-40.2%

4. Conclusions

In this work, the influence of orientation, room and window geometry, and Window to Floor Ratios (WFRs) variations has been analyzed for daylight harvesting maximization considering an academic classroom as case study. The daylight analysis, performed with a climate-based approach via DIVA simulation tool, has been carried out considering Daylight Factor (DF) and Daylight Autonomy (DA) ratios. Moreover, the energy savings, obtained by assuming different (WFRs) and two lighting systems with fluorescent and LED lamps, have been evaluated.

The main findings of this work are summarized hereinafter:

- once orientation and WFRs are fixed, the two classroom geometries (rectangular and square) do not show remarkable differences in terms of DA ratios (see Table 5). Moreover, the results show that, for daylight harvesting assessment, the DF ratio is less usable with respect to the DA ratio;
- at the same WFR, a rectangular room geometry provides better energy results if a rectangular window is chosen (cases 8_R_R_12%_S and 24_R_R_12%_S in Table 6), both for fluorescent and LED lamps. Similarly, for a square room geometry the best energy results are provided by a square window (cases 48_S_S_12%_S and 64_S_S_12%_S in Table 6);
- among all the cases, the LED lamps installation determines energy savings about equal to 26.4% with respect to fluorescent lamps;
- the best energy result (467.5 kWh/yr) is defined by the combination of rectangular classroom, rectangular south-oriented window, WFR equal to 12%, and LED lamps (case 24_R_R_12%_S in Table 6).
- a climate-based lighting simulation approach allows a proper early stage of lighting design, in order to maximize the daylight harvesting;

Based on these results, possible future developments can include a detailed discomfort glare analysis and the effects gathered by shading systems, also with reference to new CEN Daylight Standard (prEN 17037:2018) according to which the daylight should contribute significantly to the lighting requirements of any type of building.

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