General Lighting in Offices Building: Techno-Economic Considerations on the Fluorescent Tubes Replacement with LED Tubes

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Abstract

The use of LED light sources is nowadays an attractive solution because it can easily lead to lower operating costs of artificial lighting. In the last years, the replacement of fluorescent lamps with LED tubes for lighting of workplaces have been frequently proposed. The aim of the Authors is to analyze, from techno-economic's point of view, the fluorescent tubes replacement of a typical office building with LED tubes. Using the evaluation of the Lighting Energy Numeric Indicator has been possible to point out that the replacement of the fluorescent tubes allows a reduction in energy consumption for lighting higher than 50% with an obvious reduction in the annual operating cost. For the lamps replacement, in the case study have been estimated a simple payback time of less than 5 years. The methodological approach used by the Authors, although based on a case study, can be extended to numerous office buildings because the analyzed configurations (use and dimension of the rooms, type and features of the luminaires) can be considered significantly representative of this type of buildings. The choice of the LED sources that are suitable for the fluorescent lamps replacement must be preceded by a careful lighting analysis in order to ensure the compliance with the standards requirements.

Keywords: LED lighting; lamps replacement; office buildings lighting; energy consumptions evaluation; operating costs of lighting systems

1. Introduction

The attention to energy consumption due to the artificial lighting for buildings was decisively brought to the attention of the European technical community by means of the well-known European Directive 2002/91 on the energy performance of buildings. Later the European Directive 2010/31/UE has introduced the concept of "near Zero Energy Building" pointing out the importance of the calculation of the lighting energy demand for non-residential buildings. Very recently the EU Commission Recommendation 2016/1318 [1] of July 2016 reiterated the importance of the gradual transformation of existing buildings into nearly zero-energy buildings. In [1] it is indicated that the objective to be achieved in the primary energy consumption for office buildings located in the Mediterranean area is in the range of 20 to 30 kWh/m^{2}year. Nowadays, in most European office buildings, the above indicated values are reached by considering only the energy consumption due to artificial lighting [2]. Unlike what happens in residential buildings, it can be estimated that the electrical uses in well insulated office buildings account for 60 to 70% of the total primary energy consumption, while the thermal uses (i.e. heating, cooling, DHW) account for the remaining 30 to 40% [3-7].

Due to the expectation regarding the recent evolution of the technologies, the potential for energy saving deriving from a progressive replacement of lighting devices (i.e. lamps, luminaires, and control systems) is considered to be relevant [8-11]. In

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general, using new technologies both for source types and control systems, a reduction of 50% of electrical energy consumptions for an office building is considered a realistic target, these values give a clear idea of the enormous potential of artificial lighting in offices [8-11].

The remarkable evolution that involves the lighting industry has resulted in the growth of the interest in energy performance of artificial lighting systems both existing and new. The use of LED light sources is nowadays an attractive solution because it can lead to lower operating costs of lighting systems and a major sustainability, but it generally required higher initial investment [12]. In the last years the manufacturers and the maintainers frequently have proposed the substitution of fluorescent lamps with LED tubes in order to obtain an immediate reduction in energy consumption. However, in some cases such substitution may lead to lower quality of lighting and to uncomfortable non-visual effect often underestimate or ignored [13-16].

The aim of the Authors is to study, through a techno-economic analysis based on field measurements and software simulations, the lighting system of an office building equipped in the current state with fluorescent tubes, for which the replacement of lamps with LED tubes is proposed. The results of the techno-economic analysis have been discussed by using several parameters. In particular, in order to discuss the results about the energy saving due to the use of LED technology, the Lighting Energy Numeric Indicator (LENI) has been employed. This indicator was defined by the European Standard EN 15193 [17] for the purpose of providing information on energy consumptions of different lighting systems in indoor environments. In order to discuss the actual convenience of fluorescent tubes replacement with LED tubes, the Pay Back Time (PBT) and the Net Present Value (NPV) have been employed. These latter indicators are the most commonly used to economically quantify the benefits obtained by energy improvement actions [18]. The evaluation of: the operative cost saving, the expected payback time and the net present value due to the lamps replacement, has been evaluated considering the average cost per kWh of the electrical energy, the purchase and the installation costs of LED tubes and the maintenance costs over a ten-year time period. The results of the evaluations described in the paper, although based on a case study, can be extended to numerous office buildings, given that the geometry and the characteristics of use can be considered significantly representative of this type of buildings.

2. Lighting Requirements in Office Workplaces

Proper lighting is an essential aspect to fulfill important human needs: lighting should be comfortable, convey a sense of safety and not cause visual fatigue or, worse, discomfort. In a workplace these needs are represented by different basic visual requirements, i.e.: visual comfort (the workers have a feeling of well-being, this also contributes to a higher productivity level and a higher quality of work), visual performance (the workers are able to perform their visual tasks, even under difficult circumstances and during longer periods) and safety [19, 20]. To determine the fulfillment of the basic visual requirements, the evaluation of some lighting parameters, both qualitative and quantitative, should be done. The most relevant qualitative lighting parameters are specified in [20], they are: the directionality of light, the variability of light, and the flicker. They can be evaluated on the basis of the photometric features of the luminaires and on the characteristics of the lighting sources. For the quantitative lighting parameters, the following limit values are specified in function of the type of area, task or activity [20]: minimum average maintained illuminance (E_m) on the reference surface, maximum Unified Glare Rating (UGR_L), minimum illuminance uniformity (U_0) on the reference surface, and minimum color rendering index (R_a). The limit values specified in [20] are summarized in Table 1 for office workplaces. From the analysis of Table 1, it can be noticed that high values of illuminance for all the visual tasks performed at the desk are required. The required values of E_m are variable from 500 lx (reading and writing activities) up to 750 lx (technical drawing) and the required values of R_a are always above 80. The only areas, where the lighting requirements are less severe, are the circulation areas such as corridors, stairs and elevators, in which the required values are: 100 lx for E_m, 0.40 for the U_0, 40 for R_a.

Since the Authors carried out a techno-economic analysis, the compliance with the standard limit values shown in Table 1 has been verified only with the aim to identify a suitable solution for the fluorescent tubes replacement, among the LED tubes commercially available.

Table 1 Lighting requirements for office workplaces [19]

	Type of areas, task or activities	**E_m (lx)**	**U_0 (1)**	**UGR_L**	**R_a**
General areas	Circulation areas and corridors (2)	100	0.40	28	40
	Stairs, escalators, travolators (3)	100	0.40	25	40
	Elevators, lifts (4)	100	0.40	25	40
	Loading ramps/bays	150	0.40	25	40
Offices	Flying, copying, etc.	300	0.40	19	80
	Writing, typing, reading and processing (5)	500	0.60	19	80
	Technical drawing	750	0.70	16	80
	CAD work stations	500	0.60	19	80
	Conference and meeting rooms (6)	500	0.60	19	80
	Reception desk	300	0.60	22	80
	Archives	200	0.40	25	80
Surfaces	Walls (in office)	75	0.10	-	-
	Walls (in other rooms)	50	0.10	-	-
	Ceiling (in office)	50	0.10	-	-
	Ceiling (in other rooms)	25	0.10	-	-

(1) Illuminance uniformity: $U_0=E_{min}/E_m$. (2) Illuminance at floor level; Ra and UGR_L similar to adjacent areas; the lighting of exits and entrance shall provide a transition zone to avoid sudden changes in illuminance between inside and outside by day or night. (3) Requires enhanced contrast on the steps. (4) Light level in front of the lift should be at least E_m=200 lx. (5) See lighting of work stations with DSE. (6) Lighting should be controllable.

3. The Office Building Used as Case Study

The case study, analyzed by the Authors, is an office building of the School of Engineering of the University of Pisa. The building consists of three floors; the ground floor is used as a mechanic's workshop while the first and second floors are used for offices and laboratories. Overall, the first floor consists of 7 offices and 5 laboratories while the second floor consist of 5 offices and 8 laboratories (Fig. 1). For the aims of this study, the ground floor has not been considered. On each floor there are also two corridors and 3 toilets. In total, the building consists of 12 offices, 13 laboratories, 4 corridors and 6 bathrooms. An elevator and two interior stairs guarantee the vertical connections. As it can be seen from Fig. 1, the planimetric distribution of the case study (central corridor with rooms on either side) is typical of medium-large sized office buildings (like those intended for public offices).

In this paper, three rooms on the second floor (Fig. 1) have been chosen for the description of the lighting analysis: the office (O4), the laboratory (L2) and the connecting corridor (C1). These rooms are representative of the various rooms that constitute the studied office building. In the analyzed rooms (O4, L2 and C1), an extensive illuminance measurement campaign has been carried out with the objective of characterizing the daylight conditions (with various shielding systems), those of artificial lighting and integrated lighting (mix of artificial and daylight). In this paper the Authors discuss the case of artificial lighting with the use of two different light sources: fluorescent tubes and LED tubes (replacing fluorescent tubes).

3.1. Office (O4)

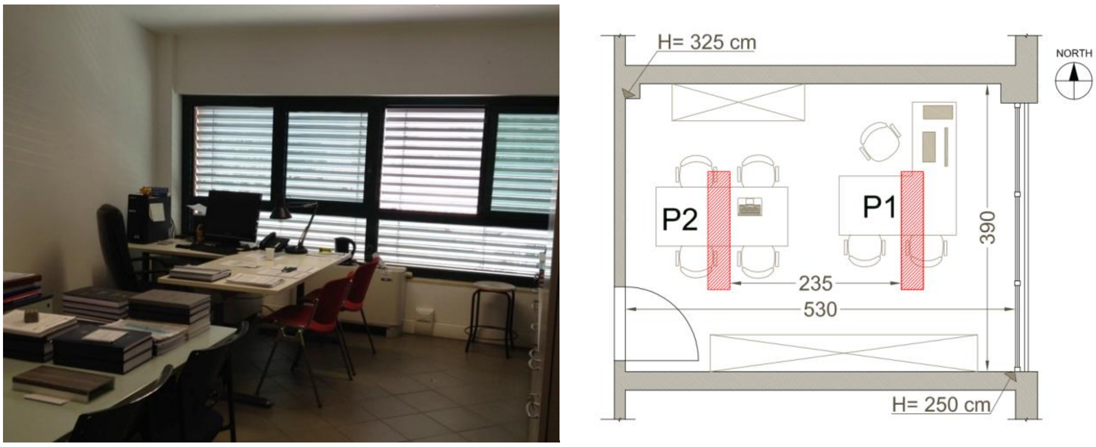
The office O4 has a net floor area of about 21 m^2 (length 5.30 m, width 3.90 m and variable height from 3.25 to 2.50 m); the windows have an overall surface equal to 5 m^2, and they are disposed on the outside vertical wall, exposed to the East (see Fig. 2(a)). The windows are equipped with external shielding systems to direct sunlight (shading with adjustable horizontal slats), which can be adjusted to obtaining a partial or complete shielding. The internal surfaces are characterized by: opaque vertical walls and ceiling plastered and painted white (with a reflection coefficient of 0.80), dark grey ceramic tile floor (with a reflection coefficient of 0.30). In the Office O4, there are a workstation (P1), used mainly for work on display screen equipment, and a table for meetings (P2), on which the main visual task is to read and write on paper.

The office is lit by ceiling mounted luminaires with reflective aluminum (Table 2). Each luminaire is equipped with two 58 W (T8) fluorescent lamps with a color temperature of 4000 K. The main technical features of the luminaires and fluorescent lamps are shown in Table 2. Table 2 also shows the main technical features of the LED tube, suitable for replacing the fluorescent lamp in the office and in the laboratory (see Section 5).

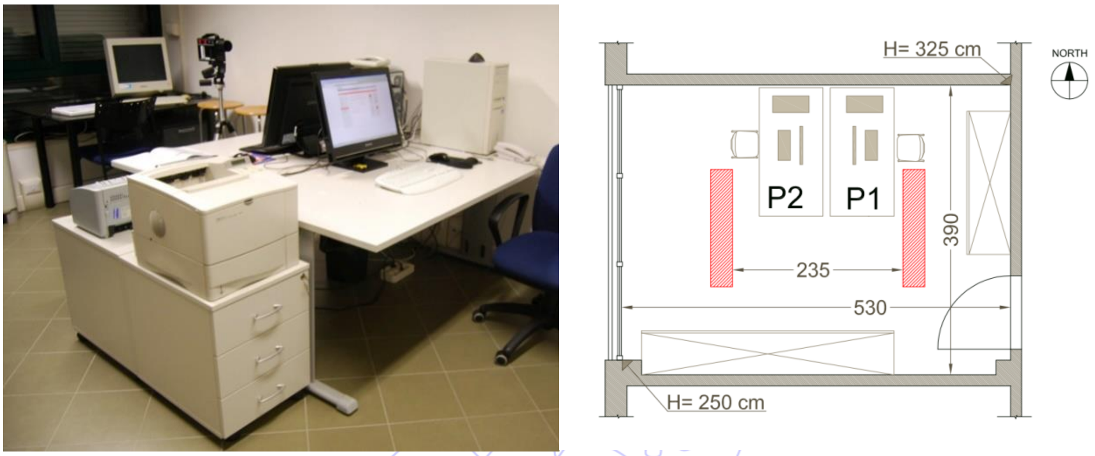
(a) External pictures

(b) floor plans

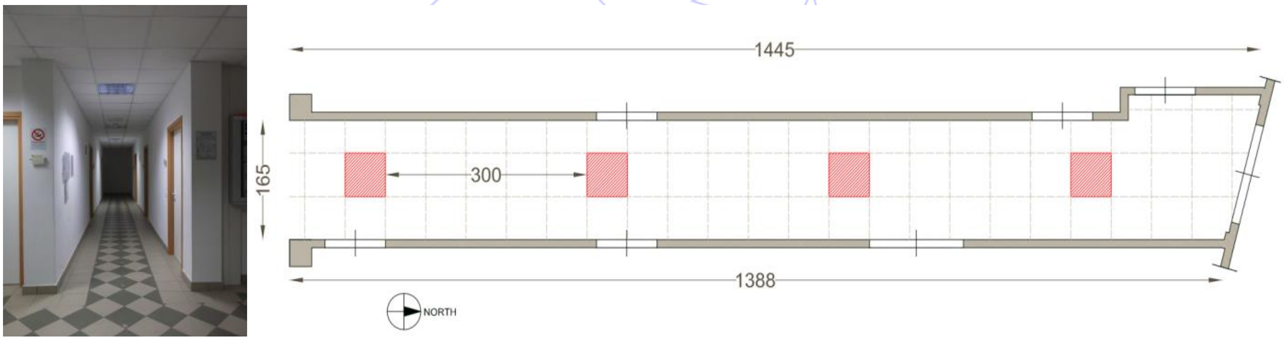
Fig. 1 Analyzed building



(a) O4



(b) Laboratory L2



(c) Corridor C1

Fig. 2 Picture and floor plan (with positions of the ceiling mounted luminaires and main dimensions of the room in centimeters)

3.2. Laboratory (L2)

In the laboratory L2 (see Fig. 2(b)) there are two workstations (P1 and P2) with display screen equipment, frequently used for calculation and simulation activities, in addition to a desk used for the measurement activity. This room has the same characteristics of the office O4 in term of: net floor area (21 m^2); windows surface (5 m^2, but exposed to the West), adjustable shielding systems, colors and materials of the interior surfaces, lamps and luminaires (see Table 2).

3.3. Corridor (C1)

The corridor C1 has a net floor area of about 24 m^2 (length 14 m, width 1.7 m, height 2.7 m) and it is devoid of windows (see Fig. 2(c)). The corridor has opaque vertical walls plastered and painted white (with a reflection coefficient of 0.80), the ceiling is made of plasterboard panels and painted white (with a reflection coefficient of 0.76) and the floor finished with stoneware grey and white tiles (with a reflection coefficient of 0.50).

The corridor is lighted by recessed luminaires installed in the ceiling and fitted with louver reflective aluminum (Table 3). Each luminaire is equipped with four 18 W (T8) fluorescent lamps with color temperature of 4000 K. The main technical features of the luminaires and of the fluorescent lamps are shown in Table 3. Table 3 also shows the main technical features of the 8 W LED tube, suitable for the replacement of the fluorescent lamp in the corridor (see Section 5).

Table 2 Lamp and luminaire features for the office O4 and the laboratory L2

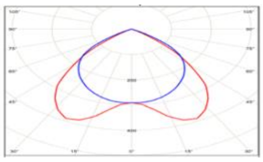
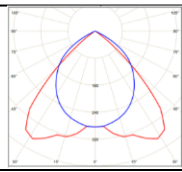
Properties of Luminaire		**Picture**	**Photometric curves**
Length	300mm		
Width	1554mm		
Height	89mm		
Optical efficiency	0.75		
CIE Flux Codes	66 99 100 100 75		
Properties of lamp	**Symbol**	**Fluorescent lamp**	**LED tube**
Length	ℓ	1500mm	1500mm
Diameter	d	26 mm (T8)	26 mm (T8)
Base		G13	G13
Nominal wattage	P	58 W	25 W
Actual wattage (lamp + power supplier)	P*	68 W	25 W
Luminous Flux	Φ_l	5200 lm	3700 lm
Luminous efficacy	η	90 lm/W	148 lm/W
Color temperature	T_K	4000 K	4000 K
Color Rendering Index	R_a	80	80

Table 3 Properties of luminaires and lamps used in the corridor C1

Properties of luminaires		**Picture**	**Photometric curves**
Length	596 mm		
Width	596 mm		
Height	80 mm		
Optical efficiency	0.68		
CIE Flux Codes	66 99 100 99 68		
Properties of lamps	**Symbols**	**Fluorescent lamp**	**LED tube**
Length	L	600 mm	600 mm
Diameter	d	26 mm (T8)	26 mm (T8)
Base		G13	G13
Nominal wattage	P	18 W	10 W
Actual wattage (lamp + power supplier)	P*	23 W	10 W
Luminous Flux	Φ_l	1350 lm	1100 lm
Luminous efficacy	η	75 lm/W	110 lm/W
Color temperature	T_K	4000 K	4000 K
Color Rendering Index	R_a	80	80

4. Technical Evaluation of the Existing Fluorescent Tubes Replacement

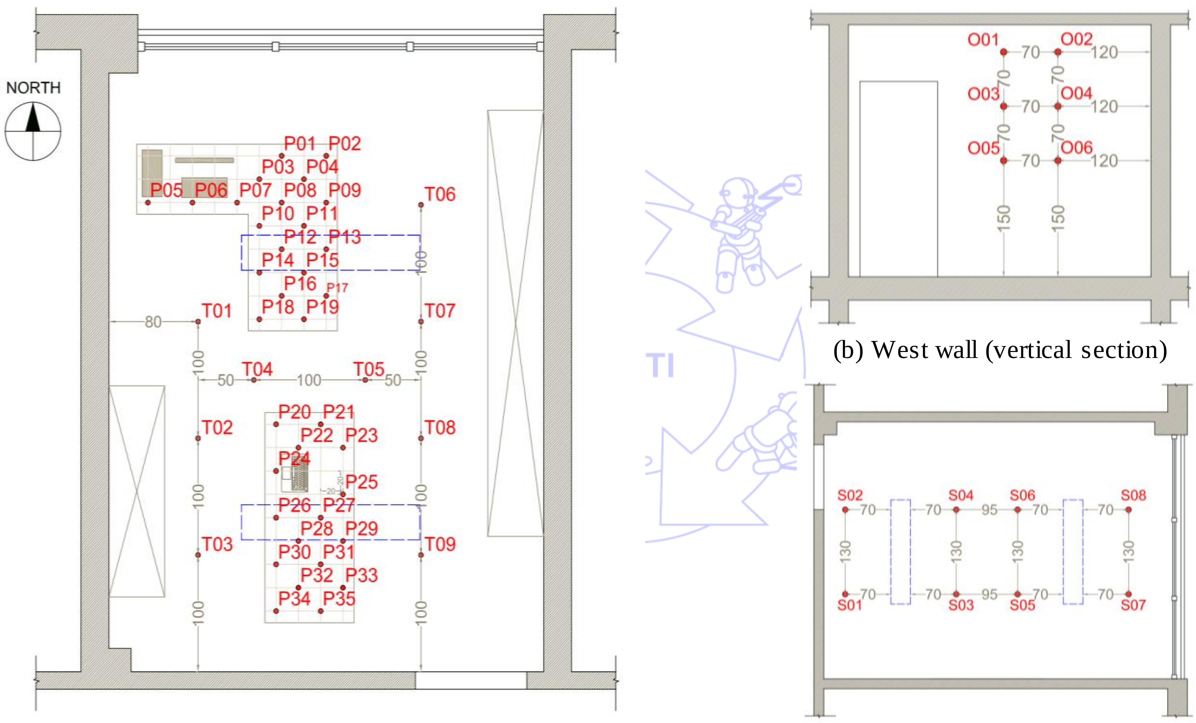
The technical evaluation of the existing fluorescent tubes replacement has been carried out in order to identify, among the LED tubes commercially available, a suitable solution. The technical evaluation, described in this paper, is limited to the verification of the compliance with the limit values shown in Table 1 of the E_m, U_0, UGR, R_a values obtained after the replacement. The E_m, U_0, UGR, values after the replacement are obtained throughout lighting simulations, by the creation of opportune models of the analyzed rooms. In order to validate the models a measurement campaign of illuminance on the most important task areas has been done in the rooms with the existing fluorescent tubes. The measurement results have been hence compared to the simulation results.

With reference to the simulation results, the luminaire installed in the analyzed rooms are equipped with shields against the direct vision of the lamps (see also picture and photometric curves in Table 2 and Table 3), for this reason, the obtained UGR values are always below the limit values specified in [20], both with fluorescent and LED tubes. The compliance of R_a

values of the LED tubes with the standard limit values has been verified by checking the technical data declared by the manufacturer (see Table 2 and Table 3).

4.1. Field measurements of illuminance

In each of the three analyzed rooms (O4, L2 and C1) illuminance measurements on the most important task areas (desks, floor, walls and ceiling) have been carried out under current state artificial lighting (fluorescent tubes). It is important to specify that for rooms where the greatest dimension in plan is 5 m (e.g. the office O4 and the laboratory L2) a minimum number of measurements equal to 8 is suggested [20], while for rooms where the greatest dimension in plan is 15 m (e.g. the corridor C1) a minimum number of 11 measurements is suggested [20]. In this study, the measurements have been carried out by preparing appropriate measurement grids (see Fig. 3) in order to obtain detailed results and make a quantitative and qualitative analysis. In particular, the following measuring points have been used: for the office (O4) 35 measuring points on the desks, 10 on the floor, 18 on the walls and 8 on the ceiling; for the laboratory (L2) 18 measuring points on the desks, 12 on the floor, 18 on the walls and 8 on the ceiling; for the corridor (C1) 35 measuring points on the floor, 48 on the walls and 8 on the ceiling.



(a) Plan (c) Ceiling (plan)

Fig. 3 Schematic representation of the measurements points for the office O4

The measurement activity has been carried out by using the portable instrument Delta Ohm HD 2102. The instrument is a data logger equipped with a photometric probe for illuminance measurements and it has an accuracy class "B" according to the Italian Technical Standard UNI 11142. The photometric probe has a spectral response in agreement with the standard photopic vision, a special diffuser for cosine correction and a measurement range from 0.1 lx to 20 klx with resolution of 1 lx.

A summary of the measurement results on the desks P1 and P2, on the floor, on the walls and on the ceiling is given in Table 4, for the three rooms O4, L2 and C1. In Table 4 the values of the average illuminance (E_m) and the illuminance uniformity (U_0) are shown for each analyzed room and for each task area (notice that $U_0=E_{min}/E_m$, where E_{min} is the smallest illuminance value measured on the task area, E_m is the average illuminance values measured on the task area).

From Table 4 it can be observed that, in the current state with the luminaires equipped with fluorescent tubes, the lighting requirements (particularly the average illuminance and the illuminance uniformity) indicated in [20] are largely satisfied, both on the desks (where the most demanding visual tasks are performed) and on other surfaces (see Table 1). This large satisfaction of normative values is not surprising, because the lamps are newly installed. In order to ensure the compliance with the minimum lighting levels (in particular illuminance level and illuminance uniformity level) required by the standard for all the time interval that elapses between two successive interventions of lamps replacement (scheduled maintenance), in the design stage it is necessary to provide an adequate over-sizing of the lighting system. The extent of the over-sizing depends on the characteristics of the considered lamp type, in particular it depends on the variation of the photometric characteristics (mainly reduction of the emitted luminous flux) in time.

Table 4 Current state (luminaires equipped with fluorescent tubes): measurement results for average illuminance (E_m) and illuminance uniformity (U_0)

		Desks		Floor	Walls				Ceiling
		P1	P2		North	South	West	East	
O4	E_m (lx)	748	739	556	186	137	116	333	113
	U_0	0.71	0.81	0.82	0.56	0.71	0.91	0.26	0.83
L2	E_m (lx)	625	565	490	163	339	89	-	105
	U_0	0.71	0.64	0.71	0.48	0.67	0.96	-	0.83
C1	E_m (lx)	-	-	404	133	-	256	286	132
	U_0	-	-	0.70	0.84	-	0.56	0.50	0.91

4.2. Lighting simulations

The lighting market generally offers more solutions, also with significantly different technical characteristics, for the replacement of each single existing fluorescent lamp. By way of example, the replacement of a 58 W fluorescent tube with 5200 lm of luminous flux (such as that indicated in Table 2) can be carried out with different LED tubes, with electric power in the range from 20 W to 30 W and with luminous fluxes in the range from 1900 lm to 4000 lm. Therefore, choosing the right lamp with which to make the replacement has to be preceded by a careful lighting analysis. For example, the choice of a lamp with too low luminous flux may result in a failure to meet the standard requirements, on the contrary, the choice of a lamp with a luminous flux comparable to that replaced may be redundant, reducing the extent of the energy saving linked to the replacement.

For the purpose of identifying the right lamps for the substitution in the case study, the authors have conducted a series of simulations using *DIALux Evo 4* lighting simulation software (www.dial.de). With this purpose, a model able to faithfully reproduce the analyzed rooms has been created, the reflection coefficients of the interior surfaces have been set, the photometric files related to luminaires have been imported and a maintenance factor (MF) equal to 0.80 has been assumed [21]. In order to validate the model, the calculation points were fixed in correspondence with all the points used for the field measurements (e.g. see Fig. 3). In these points, in the current configuration (fluorescent lamps), the measured and simulated values of illuminance were compared. The model (particularly the reflection coefficients of walls and furniture) was changed according to the results of the comparison and it was validated when a standard deviation lower than the 5% was reached.

Table 5 The case of luminaires equipped with LED tubes: simulation results for average illuminance (E_m) and illuminance uniformity (U_0)

		Desks		Floor	Walls				Ceiling
		P1	P2		North	South	West	East	
O4	E_m (lx)	569	711	472	117	114	85	171	78
	U_0	0.67	0.69	0.79	0.72	0.69	0.94	0.44	0.86
L2	E_m (lx)	680	612	414	140	269	89	-	77
	U_0	0.65	0.62	0.84	0.64	0.56	0.96	-	0.81
C1	E_m (lx)	-	-	305	130	-	258	283	125
	U_0	-	-	0.79	0.88	-	0.59	0.52	0.94

The results of the lighting simulations have allowed to identify the LED tubes indicated in Tables 2 and 3 as the most suitable solutions present in the market for the replacement in the case study. A summary of the simulation results on the desks

P1 and P2, on the floor, on the walls and on the ceiling is given in Table 5, for the analyzed rooms, similarly to what reported for the measurement results (see Table 4). From the results of the simulations is evident the respect of the standard requirements for illuminance and illuminance uniformity (see Table 5 and Table 1).

5. Energy Consumption Evaluation of the Existing Fluorescent Tubes Replacement

For each analyzed room (O4, L2 and C1), the Lighting Energy Numeric Indicator (LENI) has been evaluated in two different configurations: luminaires equipped with fluorescent lamps and luminaires equipped with LED tubes (see Section 3).

The LENI for a single room can be evaluated by the equation [17]:

$$LENI = W / A \tag{1}$$

with A (m^2) the net floor area of the room and W (kWh/anno) the total annual energy used for lighting. In particular W can be calculated as:

$$W = W_L + W_P \tag{2}$$

with W_L the annual lighting energy required to fulfil the illumination function and purpose in the room [19,20], W_P the annual parasitic energy required to provide charging energy for emergency lighting and for standby energy for lighting controls. The evaluation of W_P has been neglected in this paper because W_P does not vary with the replacement of the fluorescent lamps with LED tubes, so the simplified form: $LENI=W_L/A$ has been used.

The annual lighting energy W_L has been calculated as [17]:

$$W_L = [P_T F_C F_O (t_D F_D + t_N)] / 1000 \tag{3}$$

with P_T (W) total installed lighting power, t_D (h) daylight time usage, t_N (h) non-daylight time usage, F_C (d.u.) constant illuminance factor, F_O (d.u.) occupancy dependency factor and F_D (d.u) daylight dependency factor.

In Table 6, for each room and for the two types of analyzed lamps, the following data are shown: the number of installed lamps (N), the actual electrical power of the lamp (P*), the total electrical power needed (installed) to the lighting system (P_T), the energy required by the luminaires to ensure the adequate lighting conditions (W_L) and the LENI. The values of the daylight time usage and the non-daylight time usage, which have been used for the calculation of the LENI are [17]: t_D=2250 h and t_N=250 h. For the determination of the LENI, the dimensionless coefficients F_C, F_O and F_D have been assumed as following [17]: F_C=0.9 (absence of controlled constant illuminance systems and MF=0.8, typical value used for an office building [21]), F_O=1 (artificial lighting with centrally switching systems), F_D=1 (neglecting, in a first approximation, the contribution of the daylight). To determine the actual energy consumption due to the fluorescent lamps, the actual electrical power needed from the single lamp (P*, see Table 2 and Table 3) has been considered [17].

Table 6 Summary of the values obtained from the calculation of the LENI for the office O4, the laboratory L2 and the corridor C1

Rooms	Lamps	No. of lamps	Total luminous flux (lm)	P* (W)	P_T (W)	W_L (kWh/anno)	LENI (kWh/m^2anno)
O4 (21 m^2)	Fluorescent T8	4	20800	68	272	680	40
	LED Tubes	4	14800	25	100	250	18
L2 (21 m^2)	Fluorescent T8	4	20800	68	272	680	40
	LED Tubes	4	14800	25	100	250	18
C1 (24 m^2)	Fluorescent T8	16	21600	23	368	920	27
	LED Tube	16	17600	10	160	400	16

From Table 6, it can be seen that the replacement of the fluorescent lamps with LED tubes in the rooms allows a significant reduction of the energy consumption. This reduction (on equal terms of use) corresponds to a decrease in the LENI from 40 kWh/m^2year to 18 kWh/m^2year (reduction rate of 55%) for the rooms O4 and L2, and from 27 kWh/m^2year till to 16 kWh/m^2year (reduction rate of about 40%) for the corridor C1.

It may be of interest to see how changes the LENI in function of the hours of use of the rooms, because this parameter can significantly affect the annual energy consumption for lighting. Figure 4 shows the trend of the annual lighting energy (W_L) as a function of the annual hours of use, for different values of the F_O obtained assuming a total electrical installed power for lighting of 8.3 kW (current state, see Table 6).

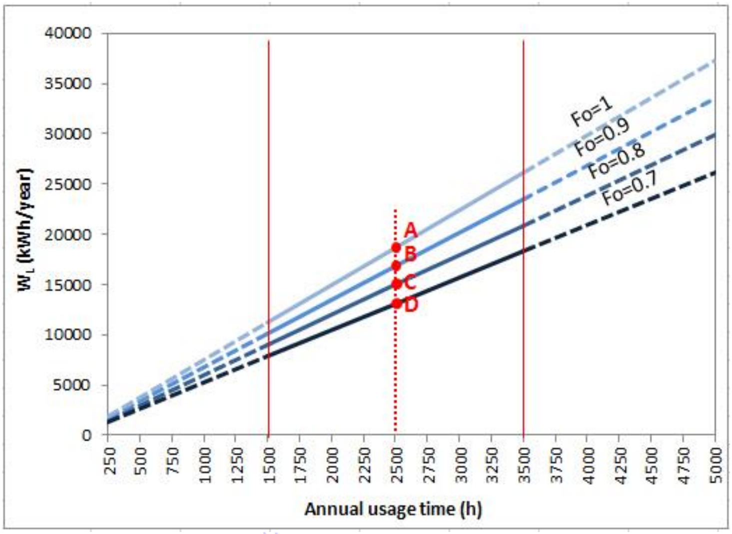


Fig. 4 Trend of W_L for the current state as a function of the annual hours of use (sum of daylight and non-daylight time) for different values F_O

In order to obtain the different solutions represented in Figure 4, the occupancy dependency factor (F_O) has been assumed equal to [17]: 1 for centralized switching system on-off (i.e. the switching system controls more than one room), 0.9 for manual switching system with on-off control in each room, 0.8 for automatic switching system with on-off control managed by detectors of presence and 0.7 for semi-automatic switching system with manual switching-on and automatic switching-off managed by detectors of presence. The annual hours of use have been varied from 250 (minimum hours of use considering only the non-daylight hours) to 5000 that is twice the hours of use for office buildings [17]. However, it can be consider that the most common use of the lighting system is included between 1500 and 3500 hours (central part of the graph). In the graph, the results obtained considering 2500 annual hours of use, as expected in [17], are also highlighted (Fig. 4, points A, B, C, and D).

6. Economical Evaluation of the Existing Fluorescent Tubes Replacement

The results of the measurements and the simulations (carried out for the three analyzed rooms) can be reasonably extended to all the rooms of the case study building, in order to do a comprehensive assessment, based on a techno-economic analysis, on whether to proceed with a systematic replacement of all existent fluorescent tubes with LED tubes.

The economic analysis has been conducted for a reference period of 10 years. Before introducing the results, it is necessary to provide information on the economic items considered for the calculation. For the new lighting system with LED tubes were calculated: the initial investment cost (I_0), the operating cost (C_o), and the maintenance cost (C_m). The parameter I_0 is given by the product of the number of installed tubes (N) and their unit cost. The evaluation has been done considering to finance the lamps replacement with own funds, so I_0 is placed to the year of the installation of the LED tubes. The parameter C_o is due to the energy consumption when the lighting system is switched-on and it depends on: the actual electrical installed power for lighting, the usage time and the hourly rate of electrical energy (estimated at 0.15 €/kWh according to the average data provided by the Energy Management Office of the University of Pisa). The parameter C_m depends on the frequency (τ) of the maintenance works for the luminaires, which are necessary in order to guarantee that the lighting requirements are satisfied (see Table 1). This parameter was evaluated as [21]: $C_m=N_r \cdot C_u$, where N_r is the number of replaced lamps during the scheduled maintenance and C_u is the all-comprehensive unit cost of lamp (that takes into account the supply, installation and disposal costs usually applied in Italy). C_o and C_m are referred to different years, respect to the year of the installation of the LED tubes (base year). For this reason, they have to be reported to the base year by discounting procedure. The discounting procedure depends on discount rate (r). The discount rate is defined as the rate at which the investment revenues and costs are discounted in order to calculate its present value. The choice of the r value should be based on the evaluator expertise and done case by case. Considering the type of intervention (lamps replacement) and the variability of electric energy costs, discount rates equal to 2% and 4% are very commonly used [18] and then they have been applied to the present study. The discounting of the individual cost parameter has been done by using the following equation: $C_d=C_k/(1+r)^k$, where C_d (€) is the discounted cash flow, C_k (€) is the cash flow expected in the k-year and r is the discount rate.

In order to consider the different usages of the lighting system, five scenarios have been defined (see Table 7). Each scenario is characterized by a different value of the annual usage time of the lighting system that varies between 1500 and 3500 hours.

To better understand the economic analysis and the Figs. 5 and 6, it is necessary to provide some indications on the maintenance cost C_m. The frequency (τ) of the scheduled maintenance varies in function of the lamp type and the environment type, it is influenced by the lighting requirements, which need to be satisfied, and by the technical data about the lamp survival and lamp lumen maintenance provided by the manufacturers. Assuming MF=0.8 (see Section 6) and the data provided by the manufacturer, for the case study the values of the maximum usage time (maximum time beyond which the lamps must be replaced) are: 8000 hours for the fluorescent tubes and 16000 hours for the LED tubes. Through these calculated values, it has been possible to evaluate τ for each scenario, the evaluation results are reported in Table 7.

Table 7 Evaluation of the frequency (τ) of the scheduled maintenance for each lighting scenario in function of the annual usage time

			Lighting Scenarios				
			1	2	3	4	5
Annual usage time		(h)	1500	2000	2500	3000	3500
τ	Fluorescent tubes	(years)	5	4	3	3	2
τ	LED tubes	(years)	10	8	6	5	4

To properly assess the economic feasibility of the replacing linear fluorescent lamps with LED tubes, it is necessary to take into account the benefits that can be achieved from the economic point of view, in addition to the initial investment, operating and maintenance costs. The expected benefits have been assessed in terms of economic benefit related to the electrical energy saving (B_o) and to the reduced maintenance (B_m) associated with the different type of lamps. The economic costs and benefits, assessed for the reference period of 10 years, are shown on an annual basis in Table 8 for the five analyzed scenarios (see Table 7). For each scenario, there are both the incoming and outgoing cash flows and it is possible to calculate the payback time (PBT) and the net present value (NPV). The intervention of refurbishment is sustainable when NPV has positive values during the analyzed period.

In Fig. 5, the trend of NPV in function of the time is shown, in the case of the refurbishment realized with an investment by own funds and a discount rate of 2%. The economic benefit, linked to the refurbishment, is higher as much as the value of NPV. The time for which NPV=0 corresponds to the PBT. In the specific case, it is possible to note that the PBT varies from a minimum of 2 years (scenario 5) to a maximum of 5 years (scenario 1). The refurbishment of fluorescent lamps with LED tubes is always profitable for each analyzed scenario because the NPV value always assumes a positive value at tenth year. In Fig. 6, for an immediate comparison of the obtained results, NPV values reached at tenth year are reported for the five scenarios and the two values of the discount rate (r). In Fig. 6, it can be observed that the replacement of fluorescent lamps with LED tubes can always be economically viable. The maximum benefit is achieved for the scenario 5, when the lighting system is exploited intensively (see also Table 7 and Fig. 5). For this scenario the reduced installed power of the LED, combined with their long life time, allows a significant reduction of the operating and maintenance costs, permitting to recover the initial investment cost in a very short time (2 years) and ensuring high benefits in economic terms. If a discount rate of 4% (instead of 2%) is considered, the same qualitative trends are obtained (see Fig. 6).

Table 8 Calculation results: evaluated technical and economical parameters in function of the considered Scenario

Scenario	I_0 (€)	C_o (€/year)	C_m (€/year)	B_o (€/year)	B_m (€/year)
1	6710	707	617	1877	282
2		942	839	2503	353
3		1178	1118	3128	471
4		1414	1342	3754	471
5		1649	1678	4380	706

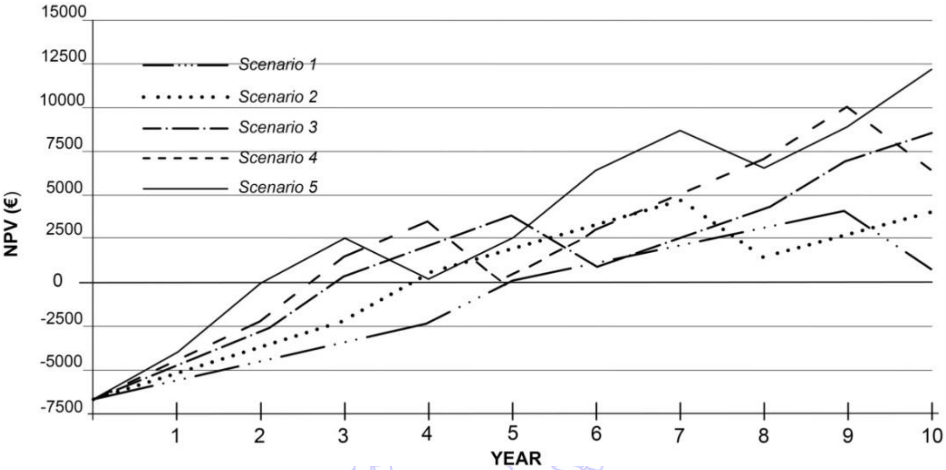


Fig. 5 Evaluation of Fluorescent tubes replacement with LED tubes: trends of NPV in function of the time (investment by own founds, r = 2%)

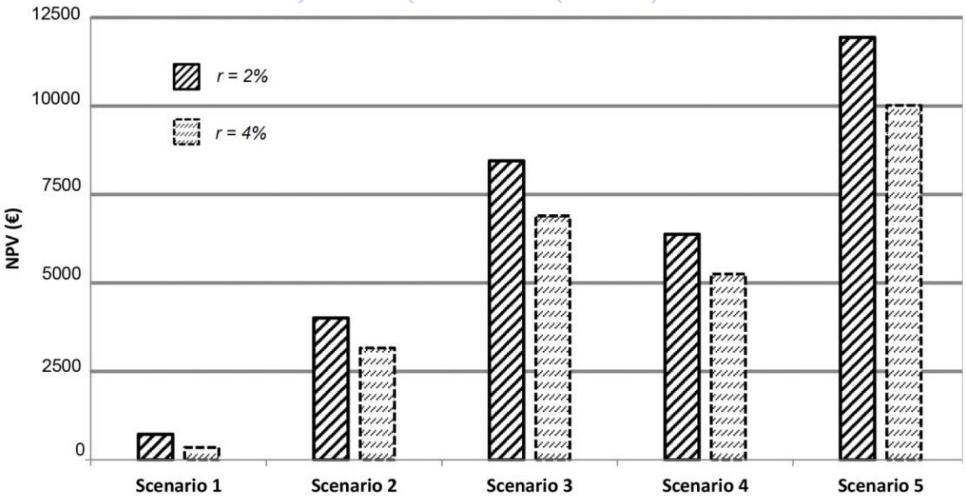


Fig. 6 NPV values obtained at tenth year for different scenario and discount rate

7. Conclusive Remarks

In this paper, the Authors evaluated the replacement of fluorescent lamps characterized by electric powers of 18 W and 58 W with LED tubes characterized by electric powers of 10 W and 25 W respectively, in an office building of the University of Pisa. The LED tubes have been selected, among the proposed solutions from the market for the replacement of existing fluorescent tubes, following a careful lighting analysis. The fulfilment of the main lighting requirements for the indoor workplaces, following the lamp replacements, has been verified through simulations using *DIALux Evo 4* lighting software.

The performance of the lighting system in the current state (with fluorescent tubes) and after the lamps replacement (with LED tubes) have been compared from techno-economic point of view, throughout the evaluation of different parameters as:

the Lighting Energy Numeric Indicator (LENI), the Net Present Value (NPV) and the Pay Back Time (PBT) related to the lamps replacement. The evaluation has been carried out considering different values of the annual usage time, from 1500 hours to 3500 hours. From the results it has been possible to point out the replacement of the fluorescent tubes with LED tubes allowing a reduction in energy consumption for lighting higher than 50% with an obvious reduction in the annual operating cost. The maximum benefit related to the lamps replacement is achieved when the lighting system is exploited intensively (annual usage time equal to 3500 hours). In this case the reduced installed power of the LED, combined with their long life time, allows a significant reduction of the operating and maintenance costs, permitting to recover the initial investment cost in a very short time (2 years) and ensuring high benefits in economic terms. The maximum benefit related to the lamps replacement may be further improved as the quality and life of LED can be improved in the future.

The results of the evaluations described in the paper, although based on a case study, can be extended to numerous office buildings, given that the geometry and the characteristics of use can be considered significantly representative of this type of buildings. However it is important to remark that, since the solution proposed by the market for the replacement of each fluorescent lamp is not unambiguous; the correct choice of the LED source must be made after a careful lighting analysis to be conducted case by case.

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