

UPCommons

Portal del coneixement obert de la UPC

<http://upcommons.upc.edu/e-prints>

Aquesta és una còpia de la versió *author's final draft* d'un article publicat a la revista *Energy Conversion and Management*.

URL d'aquest document a UPCommons E-prints:

<http://hdl.handle.net/2117/88386>

Article publicat / *Published paper:*

Casals, M., Gangolells, M., Forcada, N., Macarulla, M. (2016) Reducing lighting electricity use in underground metro stations. *Energy Conversion and Management*, 119 : 130-141. DOI: :10.1016/j.enconman.2016.04.034

© 2016. This manuscript version is made available under the CC-BY-NC-ND 3.0 license <http://creativecommons.org/licenses/by-nc-nd/3.0/>

Casals M., Gangolells M., Forcada N., Macarulla M. Reducing lighting electricity use in underground metro stations. *Energy Conversion and Management*, 2016, 119: 130–141. <doi:10.1016/j.enconman.2016.04.034>

Final version available at: <<http://www.sciencedirect.com/science/article/pii/S0196890416302746>>.

Reducing lighting electricity use in underground metro stations

Miquel Casals ^a, Marta Gangolells ^{a*}, Núria Forcada ^a, Marcel Macarulla ^a

^a Universitat Politècnica de Catalunya, Department of Project and Construction Engineering, Group of Construction Research and Innovation (GRIC), C/ Colom, 11, Ed. TR5, 08222 Terrassa (Barcelona), Spain

* Corresponding author: Marta Gangolells. Tel: (+34) 93 7398947, Fax: (+34) 93 7398101. E-mail: marta.gangolells@upc.edu

ABSTRACT

Lighting systems are usually one of the largest electrical end-uses in underground metro stations. Taking into account that budget restrictions in publicly owned companies hinder energy efficiency retrofit projects that require high initial investments, affordable energy saving strategies are needed. This paper presents a low-cost approach for reducing lighting electricity use in underground stations, without affecting passengers' comfort or the metro operator's service. For this purpose, an adaptive lighting strategy of dimming the illuminance levels of artificial light sources has been developed. Dimming controls are based on the occupancy of the station, and the preventive maintenance and cleaning cycles of the luminaires. The stations' monthly occupancy patterns are defined through the k-means clustering technique. To illustrate its effectiveness, the method was applied to 115 underground stations of the Barcelona metro network. The results revealed overall electricity savings of 255.47 MWh on a biannual basis, which represents 36.22% of the stations' baseline lighting consumption. Individual energy savings were found to range from 25 to 87.5 MWh/year in the stations of the Barcelona metro network, depending on the number and profile of station users. The research findings will undoubtedly be useful for the future energy efficiency project plans of worldwide metro operators and managers of other underground spaces.

Keywords:

lighting system, dimming, energy consumption, energy saving, underground station, metro network

1. INTRODUCTION

Building underground is becoming more common in highly congested cities, to accommodate transport infrastructures such as underground stations and public car parks, as well as premises for administrative, commercial and leisure uses. Since vertical openings and skylights are often unfeasible, artificial lighting is the only alternative that meets users' visual comfort needs. As underground facilities usually

operate for long hours, lighting systems are one of the largest electrical end-uses in these spaces.

Metro stations are large-scale underground buildings, with a high number of service hours. The energy demand is even greater because lighting systems are designed to overcome the aging and dirtiness derived from operating in a harsh environment. To ensure that the desired lighting level is maintained over a specific time period, the systems must initially be oversized, which has a substantial effect on energy consumption. In addition, illuminance levels in underground stations tend to be higher than required by regulations, to enhance passengers' comfort and sense of security. In a recent study, the average electricity consumption of an underground station was found to amount to 217.64 kWh/m²-year and the lighting system was the biggest consumer (37%) [1].

Lighting efficiency has been widely discussed in the literature from many perspectives, including system design [2], maintenance [3, 4, 5 and 6], control strategies [7, 8, 9] and cost-benefit and life-cycle analysis [10, 11]. However, the targeted buildings typically have ordinary tertiary uses, and are often administrative facilities [7, 12, 13, 14]. Most of the existing research focuses on the need for adequate control [15] of both daylight [8, 16] and occupancy [16, 17, 18] conditions. A second strategy is to undertake technology retrofits [19, 20], in which LED is of increasing interest as it is becoming a more affordable and reliable alternative [21, 22], even though it has not always proven to be worth the investment [23, 24]. Research into the lighting efficiency of underground spaces has been scarce until now [2, 23]. Shuguang [2] developed a model for tunnel lighting control systems, whereas Chueco et al. [23] focused on the evaluation of fluorescent and LED luminaires in underground mining. Within the context of underground metro stations, a notable European research project is SEAM4US - Sustainable Energy Management for Underground Stations [26]. SEAM4US revealed that a straight technology retrofit would not provide sufficient payback to justify the required initial investment, an aspect that is considered to be very important in any energy efficiency project [27]. In a context of budget restriction for publicly owned companies, finding energy efficiency measures that do not require expensive retrofits and can interoperate with existing technology is the best, and perhaps the only, alternative.

The main objective of this paper was to develop an affordable strategy for reducing lighting electricity use in underground stations, based on data mining techniques and without affecting passengers' comfort or the metro operator's service. For this purpose, dimming control based on the occupancy level of the station and preventive maintenance and cleaning cycles of the luminaires was developed. Section 2 describes the approach, and Section 3 reports its application to a case study metro network, and discusses the results. Finally, conclusions and future studies are outlined in Section 4.

2. METHODOLOGY

The methodology used in this research can be divided into four main steps:

- Definition of the dimming rationale
- Definition of station dimming schedules
- Definition of station dimming strategies

- Calculation of energy savings derived from the implementation of dimming strategies

2.1 Definition of the dimming rationale

The minimum requirements for indoor lighting are set out in international standards [28] and local regulations [29, 30]. However, during the life of a lighting installation, the light that is available for the task progressively decreases due to accumulation of dirt on the surface and aging of the equipment [31]. The rate of reduction is influenced by the type of equipment and the environmental and operating conditions. As shown in Figure 1, decay in illuminance is gradual and inevitable. Non-recoverable depreciations include ageing and fading of materials. Other depreciations can be recovered through appropriate maintenance programs, such as cleaning and relamping. The first luminaire cleaning substantially restores the initial illuminance level. When lamps are replaced and luminaires are cleaned for a second time, the cycle starts again with the initial conditions. In lighting project design, lumen depreciation caused by age or dirt is taken into account through the maintenance factor, which increases the installed lighting power requirement to ensure that minimum illuminance requirements are always met.

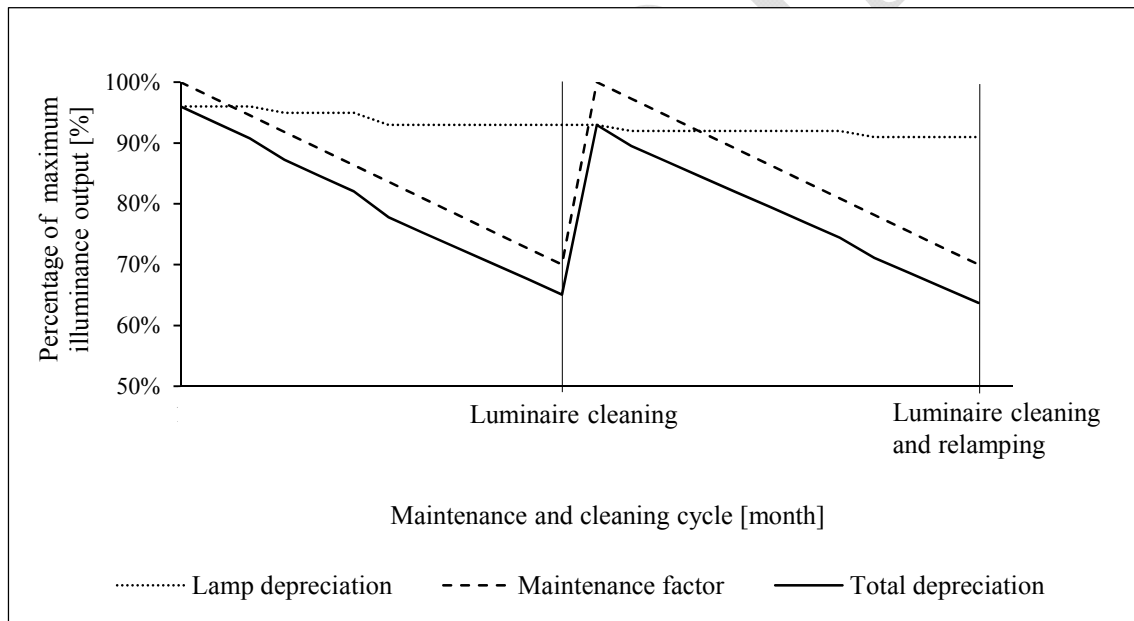


Figure 1. Variation of illuminance throughout life for artificial light sources, according to cleaning and relamping intervals

Source: adapted from [31]

In addition, metro stations are usually over-illuminated to enhance passenger safety and comfort [32], and this obviously has a substantial effect on their energy consumption [1].

Taking into account the above-mentioned considerations, the maintained illuminance (E_m) of the lighting system (expressed in lux) can be calculated according to Equation 1:

$$E_m = \frac{E_{req} \cdot CF}{MF} \quad [1]$$

Where:

E_{req} stands for the required average horizontal illuminance set out in standards and regulations (expressed in lux), defined as the value under which the average illuminance on a specified surface cannot drop, regardless of the age or condition of the installation. MF is the maintenance factor and represents the ratio of average illuminance after a certain period of use of a lighting installation (at the end of the maintenance and cleaning cycle) to the initial average illuminance obtained under the same conditions for the installation [31]. CF represents the comfort factor accommodating the extra illuminance to enhance passengers' feeling of security.

Dimming levels are defined according to two rationales. The first consideration is that the maximum average horizontal illuminance level must not be lower than the required illuminance set out in the corresponding regulation (E_{req}) at any given point of time. Thus, the illuminance level is adapted to the dirt and aging requirements as needed. In this way, the energy consumed to overcome the accumulation of dirt and aging of equipment can be kept to a minimum, especially at the beginning of the maintenance and cleaning cycles (Figure 2). The second consideration is that over-illuminance to enhance passengers' sense of security and comfort is in fact only needed in non-rush hours. Thus, the illuminance level can be lower during rush hours when the visual horizon of a travelling passenger is much shorter because of the crowd. In this way, the energy consumed to avoid passengers' feelings of fear can be kept to a minimum (Figure 2). The first consideration establishes the minimum lighting output, whereas the second consideration determines the maximum lighting output. The depreciation area in Figure 2 represents the potential savings derived from lighting system depreciation, whereas the comfort area denotes the potential savings derived from dimming the lights and still meeting the regulations.

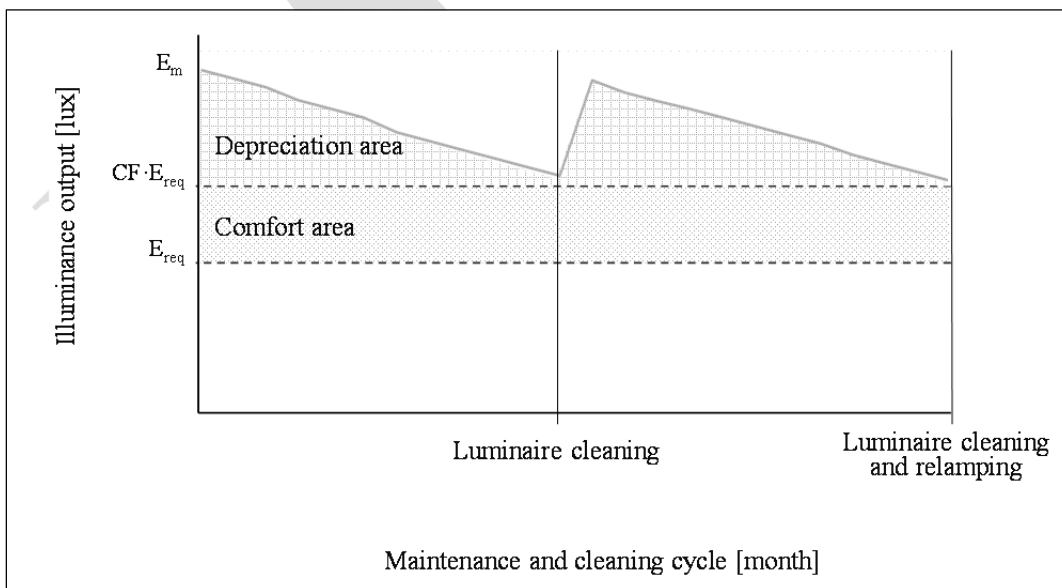


Figure 2. Dimming rationales

Source: own elaboration

According to the abovementioned dimming rationales, two occupancy thresholds are defined. The lower occupancy threshold (U_{LT}) represents the number of passengers inside the station when a higher illuminance output is needed to enhance users' safety. The higher occupancy threshold (U_{HT}) represents the number of passengers inside the station when the illuminance output can be reduced to just the required illuminance set out in the corresponding regulation. Between these values, a number of dimming steps (S) are established linearly to produce a smooth transition between lighting outputs. Dimming levels for each step, based on the number of users inside the station, can be calculated according to Equation 2:

$$\begin{cases} D_{1,m} = D_{LT,m} & \text{when } U_1 \leq U_{LT} \\ D_{S,m} = D_{HT,m} & \text{when } U_S \geq U_{HT} \\ D_{j,m} = D_{j-1,m} + \frac{D_{1,m} - D_{S,m}}{S} & \text{when } U_{LT} < U_j < U_{HT} \end{cases} \quad [2]$$

Where:

U_j represents the number of users inside a station involving a change to dimming step j (expressed as number of people), whereas $D_{j,m}$ represents the dimming coefficient corresponding to step j at month m of the maintenance and cleaning cycle, expressed as a percentage of the luminaire illuminance $[0 - 1]$. $D_{LT,m}$ is the dimming coefficient that ensures the designed comfort illuminance level at month m of the maintenance and cleaning cycle $[0 - 1]$, and $D_{HT,m}$ is the dimming coefficient that guarantees current regulations are met in terms of minimum illuminance level at month m of the maintenance and aging cycle $[0 - 1]$.

2.2 Definition of station dimming schedules

Dimming schedules are defined according to station occupancy. Although metro networks do not tend to have occupancy sensors inside the station, metro operators usually build occupancy databases to support managerial issues, such as train frequency scheduling and staff distribution. The smallest item of these databases can be expressed as $U_{y,m,dt,s,i}$, which represents the total number of passengers inside station s on the type of day dt during hour i for month $m \in M$ and year $y \in Y$. After cleansing non-meaningful or incomplete records, the stored data show that the behaviour of metro passengers depends on the day of the week and the station. Working days from Monday to Thursday show the same pattern, while Fridays, Saturdays, and Sundays and bank holidays have their own pattern.

The k-means clustering technique [33] was used to accurately identify the structure of the datasets. As expressed in Equation 3, the k-means method seeks to minimise the average squared distance between points in the same cluster. Given a set of n data points $X \subset \mathbb{R}^d$ and a number of clusters k , k centres c are chosen to minimise ϕ :

$$\phi = \sum_{x \in X} \min_{c \in C} \|x - c\|^2 \quad [3]$$

Where:

ϕ is the total squared distance between each point and its closest centre, x represents a data point, and c denotes the cluster centre.

The number of clusters k that needed to be introduced into the algorithm as an input was calculated using the WB-Index validation method [34, 35]. The WB index was obtained by running the clustering algorithm on the same data for a range of plausible cluster numbers. The lowest WB index (Equation 4) is considered to have the optimal number of clusters for that dataset.

$$WB = k \cdot \frac{SSW}{SSB} \quad [4]$$

$$SSW = \frac{1}{n} \sum_{i=1}^k \sum_{j \in C_i} \|x_j - C_{i,j}\| \quad [5]$$

$$SSB = \frac{1}{n} \sum_{i=1}^k n_i \|C_i - \bar{x}\| \quad [6]$$

Where:

k is the number of clusters, SSW denotes the sum of squares within a cluster (Equation 5), and SSB represents the sum of squares between clusters (Equation 6). n is the number of data points of the data set, x_j represents coordinate j of point x , $C_{i,j}$ denotes coordinate j of cluster centre i , n_i is the number of elements in each cluster, C_i denotes cluster i , and \bar{x} is the mean value of the entire dataset.

The process of clustering the dataset for each station and type of day revealed that most of the months of the year behave similarly. Thus, instead of considering only the records for each month, the sample can be increased to all the records belonging to the same cluster. Therefore, enhanced reliable monthly patterns were obtained through the standardised number of passengers inside station s during hour i and type of day dt in month m ($UH_{m,dt,i,s}$) (Equation 7).

$$UH_{m,dt,i,s} = \frac{1}{Y} \sum_{y=1}^Y c_{dt,i,s} \mid U_{y,m,dt,s} \subset C_{dt,s} \quad [7]$$

Where:

$U_{y,m,dt,i,s}$ represents the total number of passengers inside station s on type of day dt during hour i for month m and year y , and Y denotes the number of years considered.

2.3 Definition of station dimming strategies

Dimming controls are set in accordance with the granularity of the occupancy database. The dimming coefficient for station s at hour i , on type of day dt and in month m ($D_{m,dt,i,s}$) can be calculated according to Equation 8:

$$D_{m,dt,i,s} = \begin{cases} D_{1,m} = D_{LT,m} & \text{if } UH_{m,dt,i,s} \leq U_{LT} \\ D_{j,m} = D_{j-1,m} + \frac{D_{1,m} - D_{S,m}}{S} & \text{if } U_{LT} < UH_{m,dt,i,s} < U_{HT} \text{ and } U_j > U_{j-1} \\ D_{j,m} = D_{j-1,m} - \frac{D_{1,m} - D_{S,m}}{S} & \text{if } U_{LT} < UH_{m,dt,i,s} < U_{HT} \text{ and } U_j < U_{j-1} \\ D_{S,m} = D_{HT,m} & \text{if } UH_{m,dt,i,s} \geq U_{HT} \text{ or the station is closed} \\ & \text{but some tasks are carried out} \end{cases} \quad [8]$$

Where:

U_j represents the number of users inside a station, involving a change to dimming step j (expressed as number of people), whereas $D_{j,m}$ represents the dimming coefficient corresponding to step j at month m of the maintenance and cleaning cycle, expressed as a percentage of the luminaire illuminance $[0 - 1]$. $UH_{m,dt,i,s}$ denotes the standardised average number of users inside station $s \in L$ during hour i for month m (expressed as number of users). U_{LT} is the lower occupancy threshold (expressed as number of users), and $D_{LT,m}$ is the dimming coefficient that ensures the designed comfort illuminance level at month m of the maintenance and cleaning cycle $[0 - 1]$. U_{HT} is the higher occupancy threshold (expressed as number of users), and $D_{HT,m}$ is the dimming coefficient that guarantees that the current regulations on minimum illuminance level are met at month m of the maintenance and aging cycle $[0 - 1]$. S represents the number of dimming steps.

As shown in Figure 3, the dimming coefficient ensures that the designed comfort illuminance level is achieved at month m of the maintenance and cleaning cycle, when the standardised average number of users inside station $s \in L$ during hour i for month m is below the lower threshold. However, the dimming coefficient also guarantees that current regulations on minimum illuminance level are met at month m of the maintenance and aging cycle, when the standardised average number of users inside station $s \in L$ during hour i for month m is above the higher threshold or the station is closed. In between, the dimming coefficient corresponding to step j at month m of the maintenance and cleaning cycle is in accordance with the number of users inside a station. Figure 3 highlights the role of the number of dimming steps in the suggested dimming strategy. A higher number of steps allows better adjustment of dimming to the station's profile of users. Shaded areas in Figure 3 represent the achieved energy savings. The optimal number of dimming steps is set to be the one providing more than 0.02% of savings, compared to the savings provided when one step less is used. The precision level can be modified according to metro operator preferences. As shown in Figure 5, higher precision levels would entail more dimming steps.

$$S_{opt} \quad \text{when} \quad \frac{Sav_{mn \ i+1} - Sav_{mni}}{Sav_{mni}} < 0.02\% \quad [9]$$

Where:

S_{opt} represents the optimum number of dimming steps (expressed in units), $Sav_{mn \ i+1}$ denotes the energy savings provided by all the stations of the metro network,

considering $i+1$ steps (expressed in kWh) and $Sav_{mn\ i+1}$ corresponds to the energy savings provided by all the stations of the metro network, considering i steps (expressed in kWh).

POSTPRINT

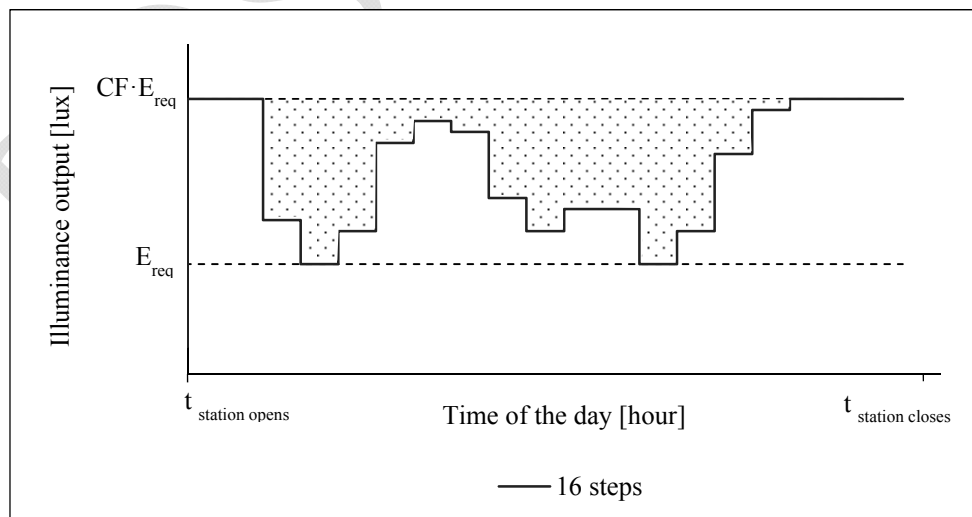
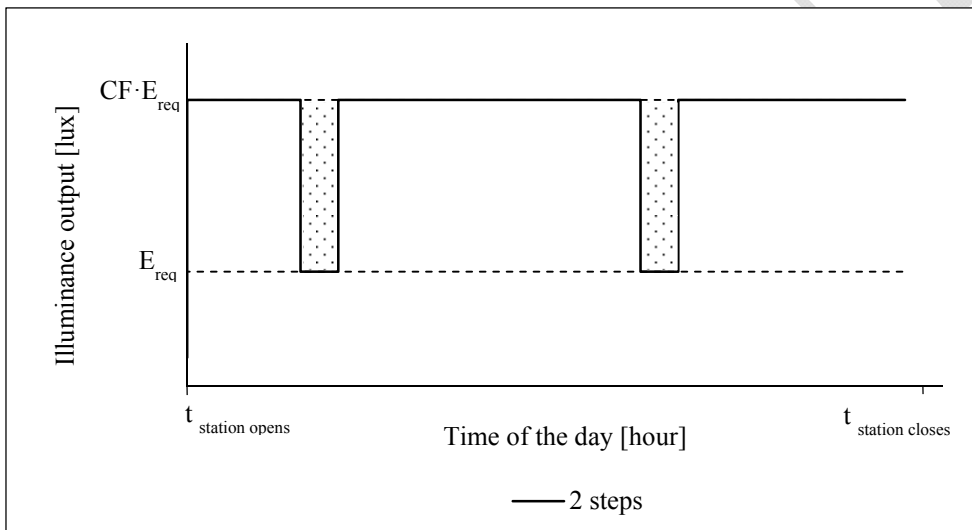
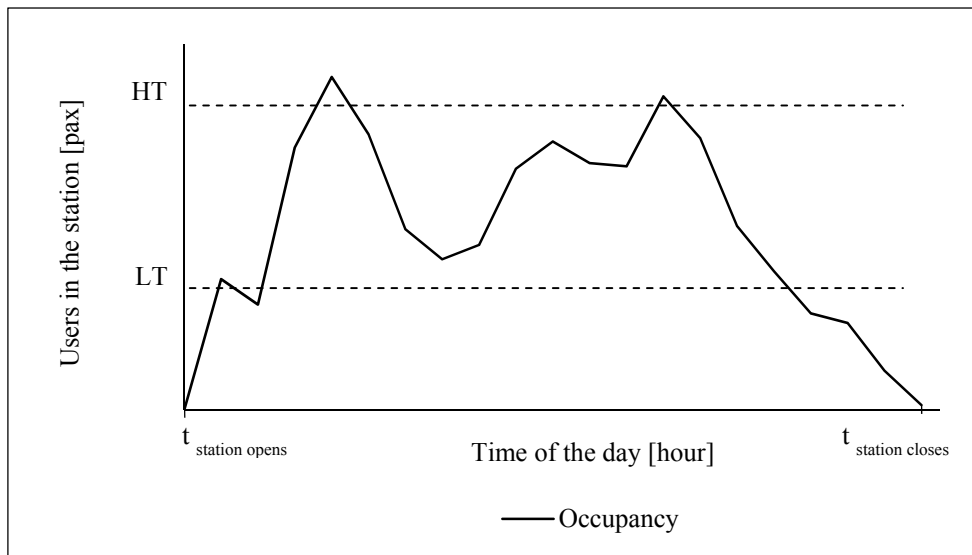


Figure 3. Illuminance output behaviour, depending on the number of dimming steps (two steps versus sixteen steps) for a given month of the maintenance and cleaning cycle

Source: own elaboration

The dimming level in each step depends on the point of time in the cleaning and maintenance cycle. By way of example, Figure 4 shows the percentage of illuminance output in step one. The first step at month 9 involves having 88.02% of the lighting output, whereas at month 13, the same step involves having 68.81% of the lighting output.

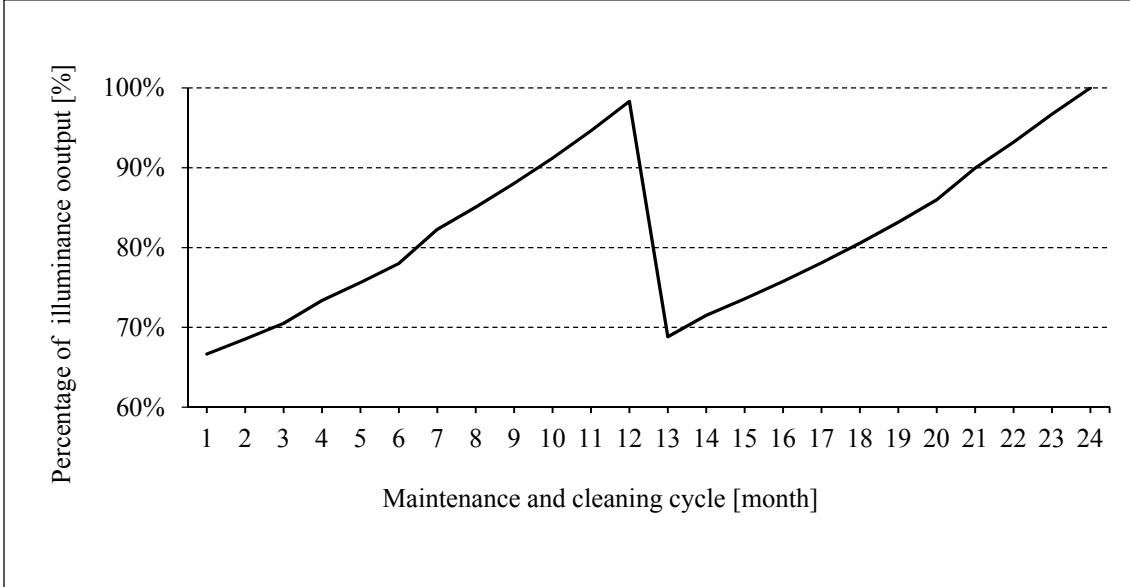


Figure 4. Dimming values during step one, according to the point of time of the maintenance and cleaning cycle
Source: own elaboration

2.4 Calculation of the energy saving derived from the implementation of dimming strategies

Energy savings are the calculated difference between the energy spent by the lighting system while operating with the designed dimming strategies, and the amount of energy that the lighting system consumes in the absence of dimming control during the entire maintenance and cleaning cycle (Equation 10).

$$Sav_s = \sum_{m=1}^M \frac{d_m}{28} \sum_{dt \in DT} \alpha_{dt} \cdot \sum_{i=1}^{24} \delta_i \cdot P_s (1 - D_{m,dt,i,s}) \quad [10]$$

Where:

Sav_s represents the energy savings provided by the lighting system for station s during a period of M months (expressed in kWh), d_m denotes the number of days of month m in the Gregorian calendar, α_{dt} is the coefficient accounting for the number of days dt in a month of four weeks (Equation 11) and δ_i is the coefficient accounting for the percentage of lighting appliances that are working (Equation 12, where PL stands for the percentage of lights switched on when the station is closed). P_s denotes the power of the lighting subsystem of station s expressed in kW, and $D_{m,dt,i,s}$ is the dimming coefficient for station s , at hour i , on the type of day dt in month m .

$$\alpha_{dt} = \begin{cases} 16 & \text{if } dt \equiv \text{Monday to Thursday} \\ 4 & \text{otherwise} \end{cases} \quad [11]$$

$$\delta_i = \begin{cases} 1 & \text{if station is open, at hour } i \\ PL & \text{if station is closed, at hour } i \end{cases} \quad [12]$$

The savings provided by all the stations of the metro network expressed in kWh (Sav_{mn}) can be calculated according to Equation 13:

$$Sav_{mn} = \sum_{i=1}^n Sav_s \quad [13]$$

Where:

Sav_s corresponds to the energy savings provided by the suggested dimming strategy for station s during a period of M months (expressed in kWh).

3. CASE STUDY AND DISCUSSION OF RESULTS

The approach was applied to those underground stations of the Barcelona metro network that are not fully automatically operated (115). On working days, stations open at 5:00 and close at 24:00. On Fridays, the service is extended until 2:00 in the early morning. During the weekends, the service is uninterrupted, from Saturday at 5:00 until Sunday at 24:00.

The underground stations are illuminated by T8 fluorescents lamps with standard electronic ballasts. The lighting system works on a static time schedule, regardless of the number of passengers inside the stations. All the lights remain on when the stations are open (150 hours per week). When stations are closed and for safety reasons, 25% of the fluorescent lamps remain on. Required lamps are also switched on when stations are closed but maintenance, cleaning or other similar tasks are being performed. Therefore, 25% of the lighting system in Barcelona metro stations works 24/7 all year, whereas the rest of the system works at least during 83.3% of the time. These operating conditions, combined with a harsh environment, require thorough maintenance policies. Along the lines of other metro networks, current maintenance practices in the Barcelona metro network consist of changing the lamps every 24 months. Luminaire cleaning is scheduled every 12 months, in the middle of the relamping cycle.

Input parameters were defined based on the results of an on-site survey and according to the recommendations of the metro operator's experts (Table 1). Table 2 shows the illuminance requirements for underground stations, depending on the type of area and according to international and national requirements [28, 30].

Parameter	Value
Percentage of lighting appliances working (δ_i)	0.25
Comfort factor (CF)	1.20
Maintenance factor (MF)	0.64
Lower threshold of passengers inside the station (LT)	20 passengers
Higher threshold of passengers inside the station (HT)	50 passengers

Table 1. Dimming and lighting calculation parameters

Area usage	I_{req} [lux]
Platform, edge	200
Platform, general	150
Ticket-selling machines and ticket validation	300
Halls	200

Table 2. Illuminance requirements for underground stations depending on the type of area

Source: adapted from [28, 30]

First, a whole-network analysis was conducted to compare the energy savings provided by a range of dimming steps (1-20) using Equation 9. In light of the results for all the stations in the Barcelona metro network (Figure 5), a 16-step policy was adopted, as the savings derived from including one more step were found to be almost insignificant (0.018%). Taking into account that the relation between the step and the dimming value is not static over time, Figure 6 shows dimming levels depending on the month of the cleaning and maintenance cycle for the 16 steps.

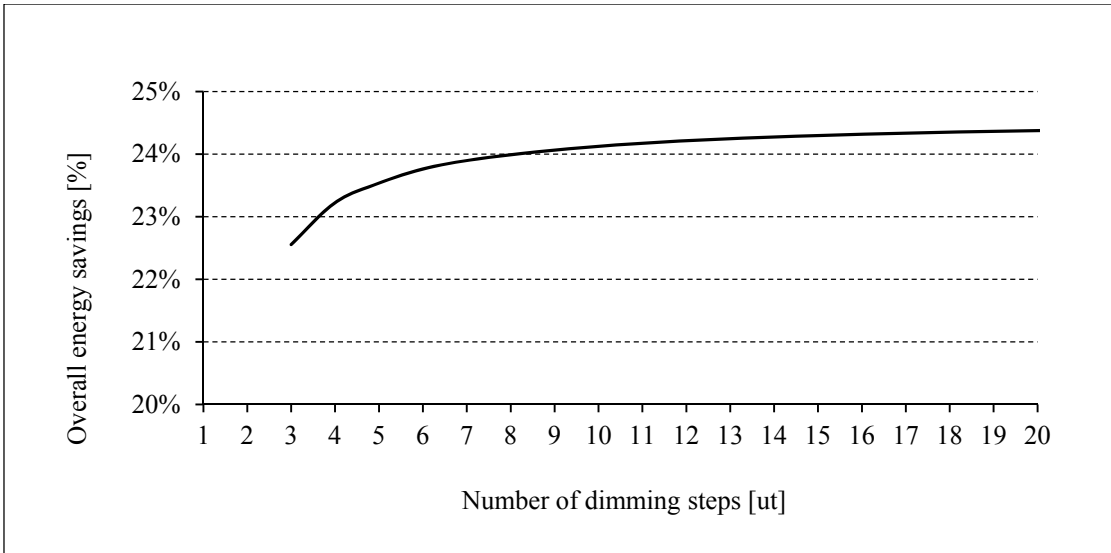


Figure 5. Energy savings in relation to baseline lighting consumption in all the stations of the Barcelona metro network, depending on the adopted number of dimming steps
Source: own elaboration

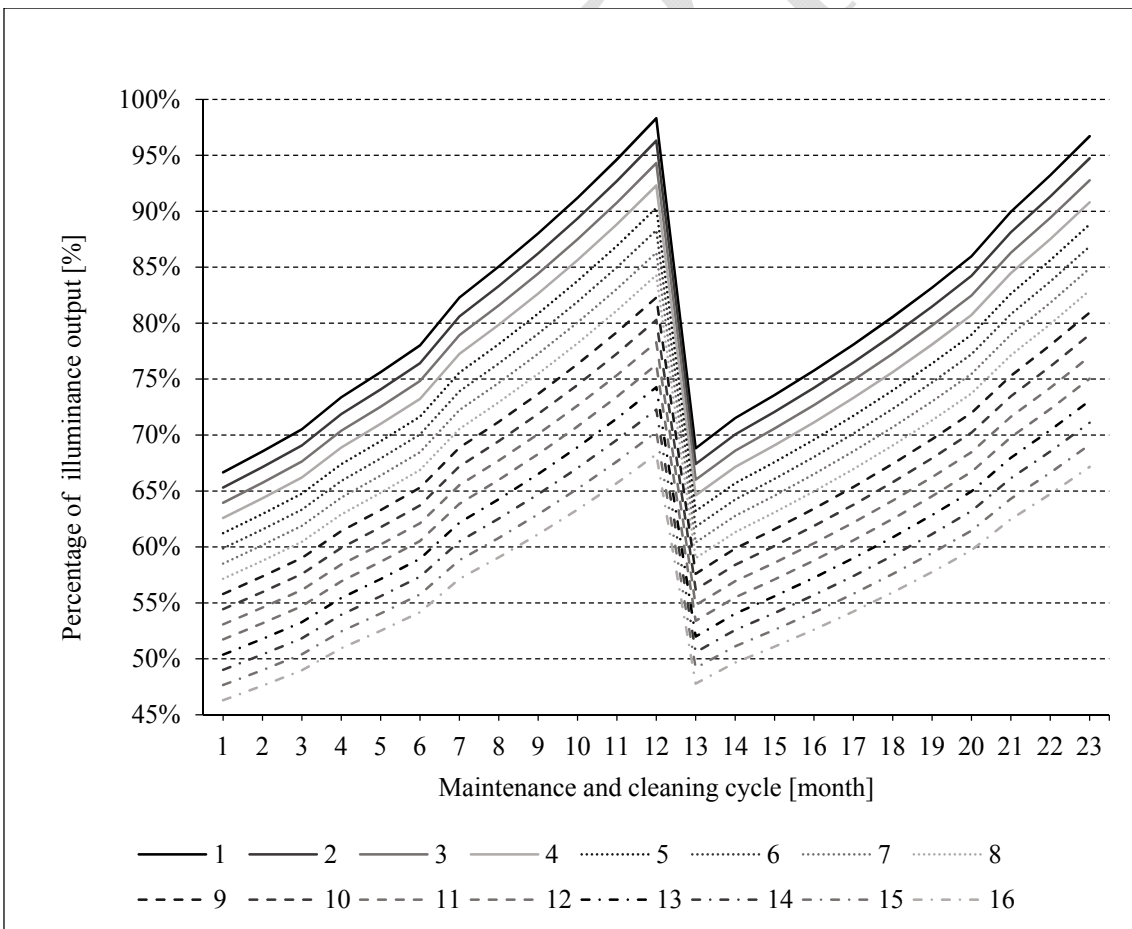


Figure 6. Dimming values for steps 1 to 16 according to the point of time in the maintenance cycle
Source: own elaboration

Station dimming schedules were defined using hourly data provided by the metro operator covering 5 years (2010, 2011, 2012, 2013 and 2014). In order to make sure that the dataset met the necessary standards of data quality, data provided by the metro operator was first pre-processed station by station, and anomalies were detected and excluded (Figure 7).

POSTPRINT

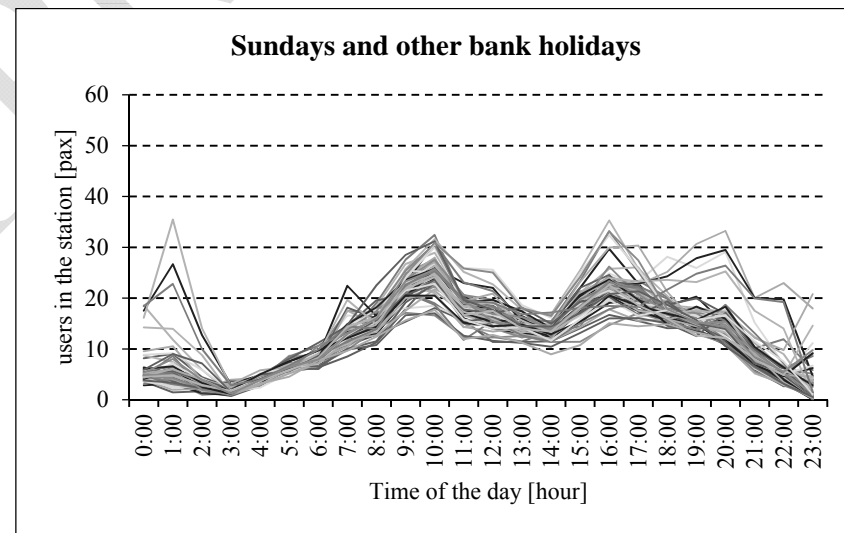
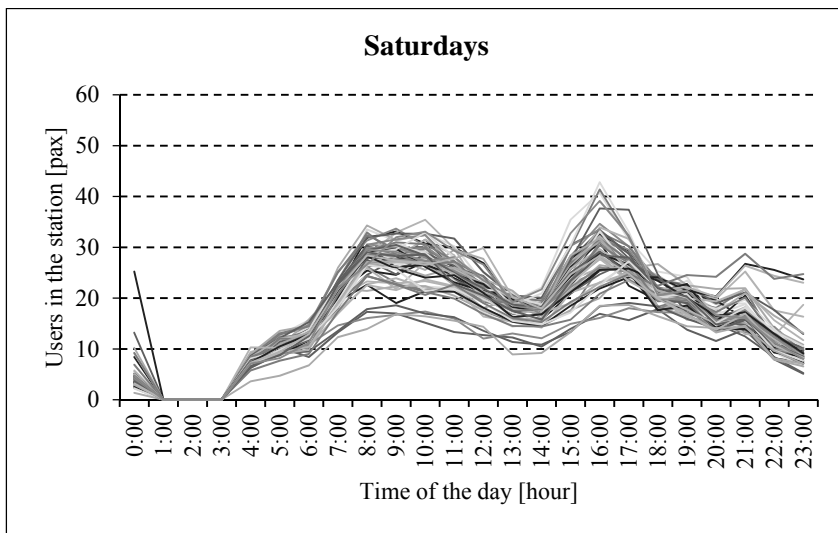
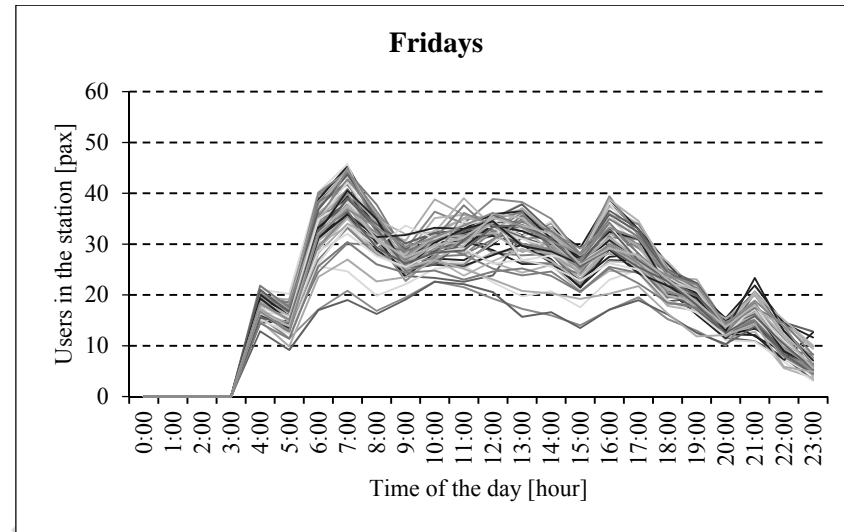
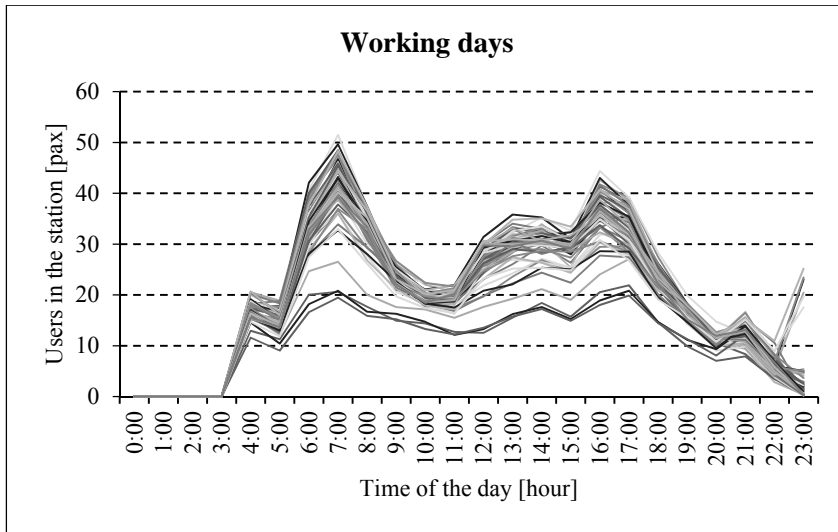


Figure 7. Cleansed daily profiles of the number of passengers in a given underground station during (1) working days, (2) Fridays, (3) Saturdays and (4) Sundays and bank holidays considering all the months of years 2010, 2011, 2012, 2013 and 2014

Source: own elaboration

Following the suggested method, the k-means algorithm (Equations 3,4, 5, 6 and 7) was used to identify the monthly patterns related to working days, Fridays, Saturdays, and Sundays and holidays for each underground station of the Barcelona network. By way of example, and for a given station of the Barcelona metro network, Table 3 shows the appropriate number of clusters according to the WB-Index procedure for each type of day. The lowest WB index is considered to have the optimal number of clusters for that dataset. Therefore, underlined numbers in Table 3 reveal that, for the case study station, the optimal number of clusters for working days, Saturdays, and Sundays and bank holidays datasets is 2, whereas the optimal number of clusters for the Fridays dataset is 3. Figure 8 shows the centroids with minimum WB-index for the working days dataset, whereas Figure 9 shows the centroids with minimum WB-index for the Fridays dataset.

Type of day	WB-Index by cluster number								
	2	3	4	5	6	7	8	9	10
Working day	<u>2.47</u>	2.51	2.51	2.82	3.18	3.43	3.77	4.02	4.40
Friday	3.03	<u>2.81</u>	3.54	3.50	4.01	4.17	4.71	5.18	5.46
Saturday	<u>2.51</u>	2.97	3.68	4.52	4.90	4.87	5.41	5.98	6.51
Sunday and bank holiday	<u>3.24</u>	3.56	4.00	4.87	5.74	5.98	6.47	7.02	6.73

Table 3. WB-Index obtained for a given station of the Barcelona metro network for each type of day

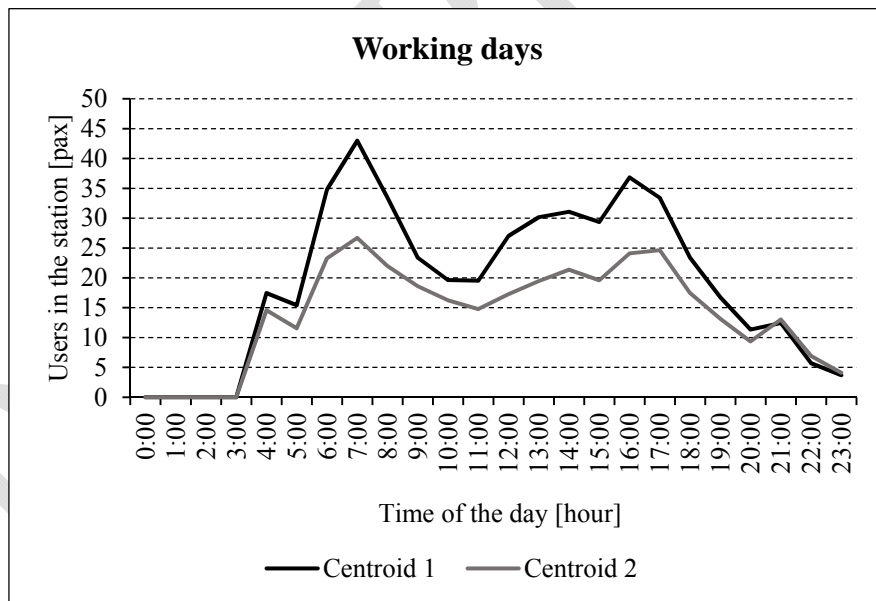


Figure 8. Centroids with minimum WB-index for the working days dataset in a given station of the Barcelona metro network

Source: own elaboration

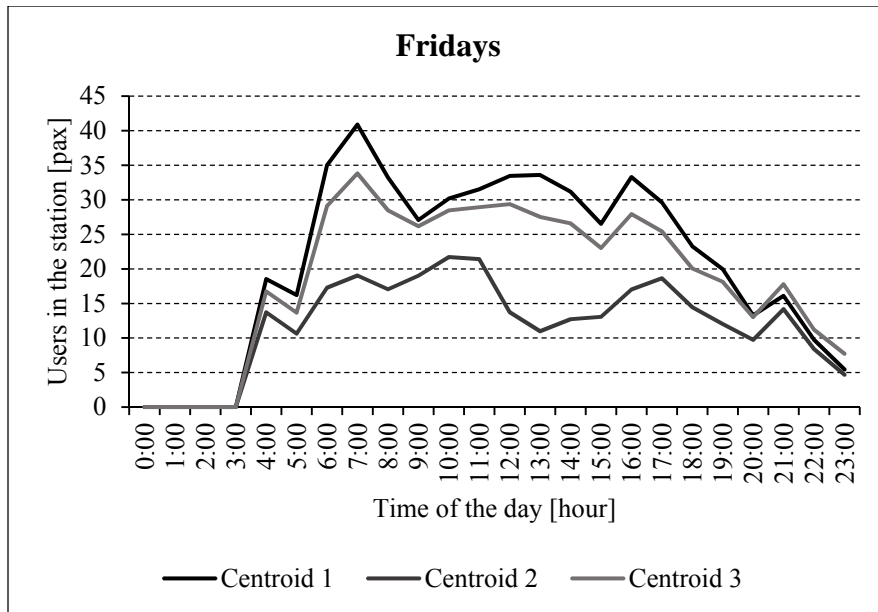


Figure 9. Centroids with minimum WB-index for the Fridays dataset in a given station of the Barcelona metro network
Source: own elaboration

Table 4 shows how expected seasonal behaviour is observed in a given station of the Barcelona metro network. Centroid number 2 is associated with August, which is a holiday period for most inhabitants of Barcelona. For each monthly record with an assigned centroid, the standard prototyped values for a given month are calculated by linearly weighting the centroid values.

Year	Month											
	January	February	March	April	May	June	July	August	September	October	November	December
2010	1	1	1	1	1	1	1	2	1	1	1	1
2011	1	1	1	1	1	1	1	2	1	1	1	1
2012	1	1	1	1	1	1	1	2	1	1	1	1
2013	1	1	1	1	1	1	1	2	1	1	1	1
2014	1	1	1	1	1	1	1	2	1	1	1	1

Table 4. Assigned centroids for the working days of a given station of the Barcelona underground metro network as a result of the k-means method for the evaluated period, for k=2

The analysis identified 1,190 centroids showing the hourly number of users inside the station for the 115 stations of the Barcelona underground metro network

(Table 5). Most of the analysed stations were found to have 3 centroids for weekdays, 3 centroids for Fridays, 2 centroids for Saturdays, and 2 centroids for Sundays and bank holidays.

Stations*	Number of assigned centroids			
	Working days	Fridays	Saturdays	Sundays and bank holidays
Stations 122, 126, 138, 216, 226, 314, 324, 326, 327, 335, 419, 422, 513, 526, 531	2	2	2	2
Stations 222, 315, 325	2	2	2	3
Station 130	2	2	2	7
Station 321	2	2	3	2
Station 225	2	2	3	3
Station 128	2	2	3	7
Stations 112, 115, 336, 427, 514	2	3	2	2
Station 328, 519	2	3	2	3
Station 510	2	3	3	3
Station 334	2	4	2	3
Stations 116 , 125, 213, 330, 331, 425	3	2	2	2
Station 515, 417, 420	3	2	2	3
Station 320	3	2	2	4
Station 113	3	3	2	2
Stations 118, 119, 121, 123, 129, 132, 133, 136, 137, 211, 215, 217, 219, 220, 223, 224, 318, 319, 322, 337, 414, 423, 429, 430, 431, 432, 433, 511, 518, 521, 528, 530	3	3	2	2
Station 120, 332, 434, 520, 522	3	3	2	3
Station 212, 316	3	3	2	4
Station 111, 218, 415, 524, 525, 527, 529	3	3	3	2
Station 323, 426	3	3	3	3
Station 517	3	3	3	4
Station 214	3	3	3	7
Station 509	3	3	4	2
Station 416	3	4	2	2
Station 127, 516	3	4	2	3
Station 329, 428	3	4	3	2

Stations*	Number of assigned centroids			
	Working days	Fridays	Saturdays	Sundays and bank holidays
Stations 117, 139, 140, 424	4	2	2	2
Station 317	4	2	2	3
Stations 135, 221, 413	4	3	2	2
Station 418	4	3	3	2
Station 124	4	3	4	3
Station 333	4	4	2	2
Station 131	4	4	3	3
Station 114	4	4	4	4
Station 512	4	4	5	3
Station 134	5	2	3	3
Station 421	6	2	2	2

* According to internal metro operator codes for the stations.

Table 5. Number of assigned centroids for working days, Fridays, Saturdays, and Sundays and bank holidays for the 115 stations of the Barcelona underground metro network

Dimming policies were defined for each hour, type of day and month by comparing the standardised schedules with dimming steps (Equation 8). By way of example, and for a given station in the Barcelona metro network, Figure 10 shows the number of users for a working day in February, and Figure 11 displays the corresponding dimming schedules. A lower dimming step indicates a higher illuminance output (i.e. less dimming), while a higher number indicates that lights can be dimmed more, which means that the number of people expected to be in the station is also higher (see Figure 6 for the step-dimming correlation). Figure 12 shows the percentage of the maximum illuminance output for the same station in the Barcelona metro network in a working day of month 2 (first February of the maintenance and cleaning cycle), whereas Figure 13 shows the same figure but for month 14 (second February of the maintenance and cleaning cycle). Finally, Figure 14 illustrates the percentage of energy savings provided by the approach on a two-year basis for a working day in February.

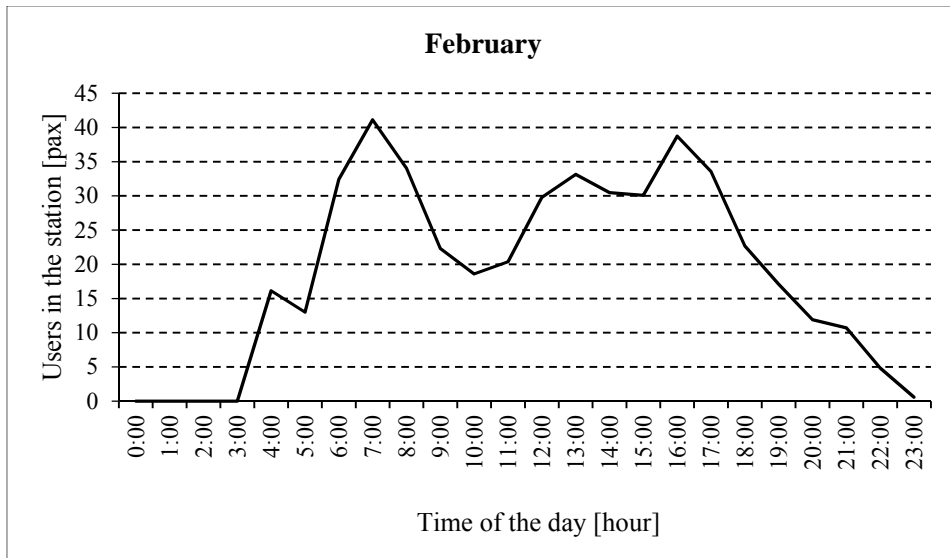


Figure 10. Daily profile of the number of users in a given station of the Barcelona metro network on a working day in February

Source: own elaboration

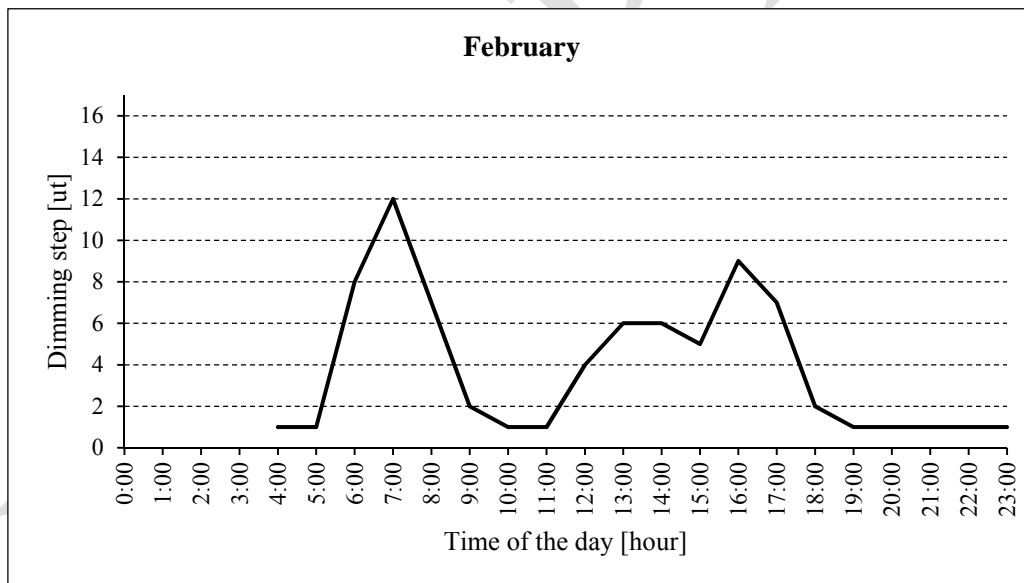


Figure 11. Dimming step for the same station of the Barcelona metro network on a working day in February

Source: own elaboration

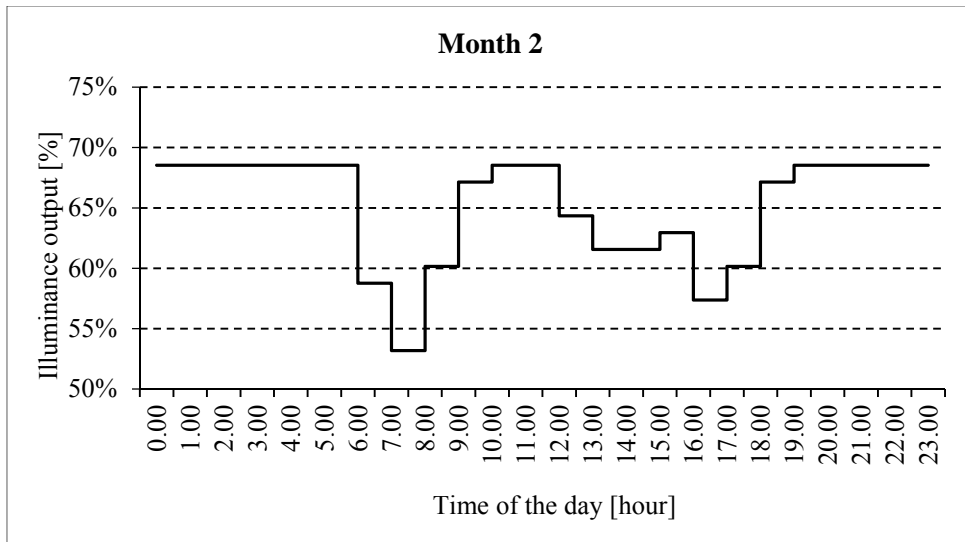


Figure 12. Percentage of illuminance output for the same station of the Barcelona metro network on a working day of month 2 (first February of the maintenance and cleaning cycle)

Source: own elaboration

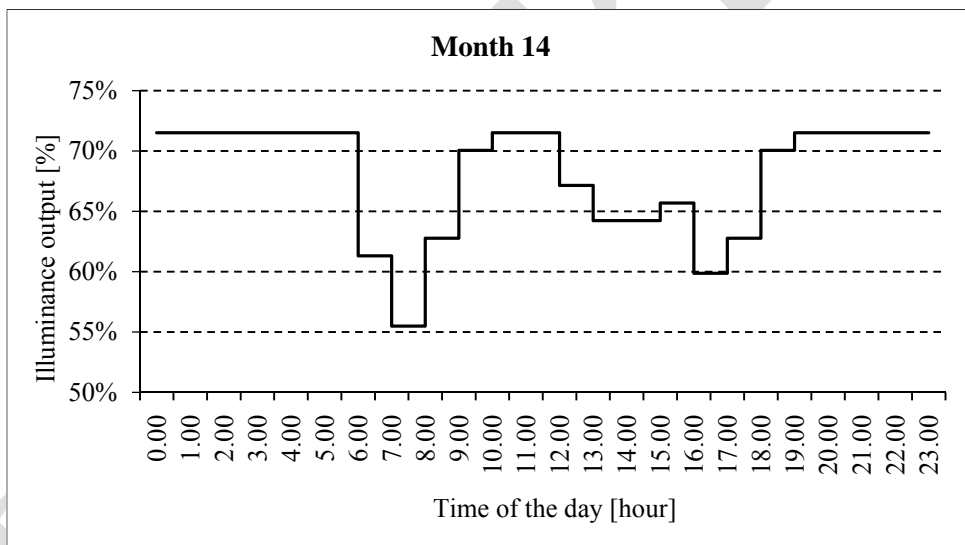


Figure 13. Percentage of illuminance output for the same station of the Barcelona metro network on a working day of month 14 (second February of the maintenance and cleaning cycle)

Source: own elaboration

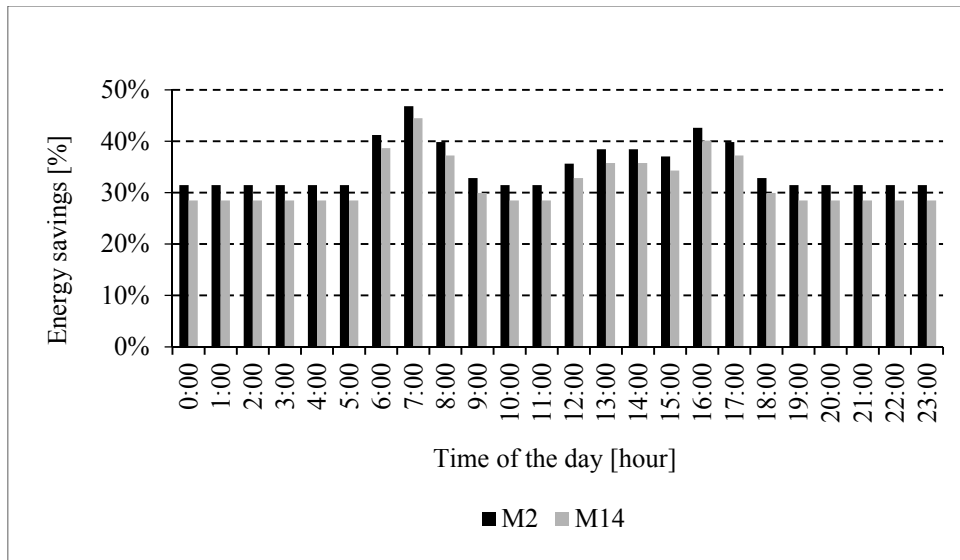


Figure 14. Percentage of energy savings for the same station of the Barcelona metro network on a working day of M2 and M14 of the maintenance and cleaning cycle

Source: own elaboration

Energy savings for all the underground stations were calculated according to Equations 10 and 13 for a two-year period, assuming that the maintenance cycle starts in January. The simulation of dimming strategies in all the stations of the Barcelona metro network was found to provide an energy saving of 255.47 MWh in two years, which represents 36.22% of the baseline lighting consumption. As shown in Figure 15, the energy savings in a given station were found to range between 50 and 175 MWh on a two-year basis, depending on the corresponding occupancy patterns. In general, the stations showing higher energy savings were those with higher occupancy maintained over time. As shown in Figure 16, expected savings were up to 33% when the number of weekly users in the station was around 100,000.

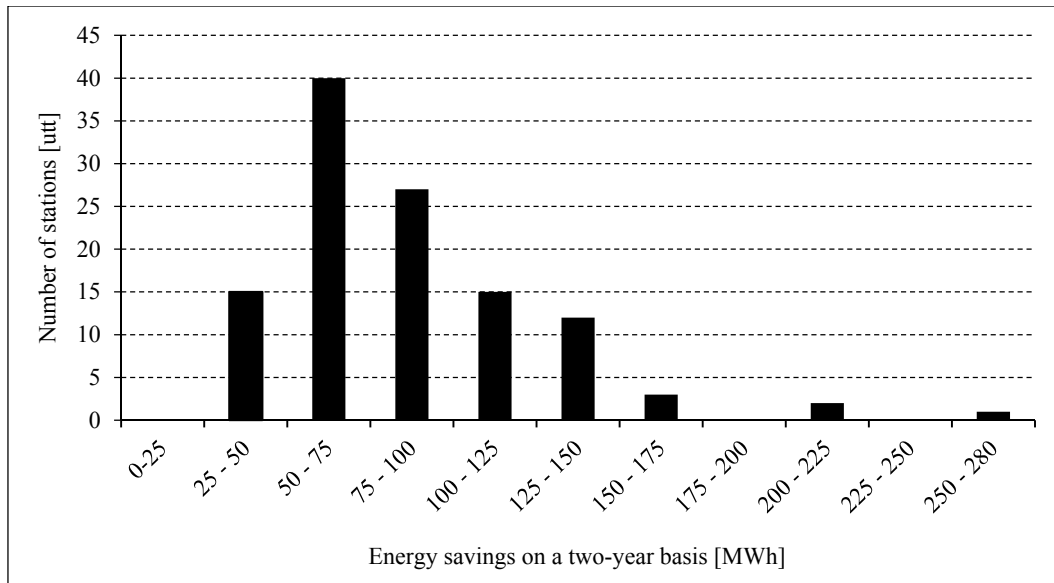


Figure 15. Distribution of underground stations of the Barcelona metro network, according to the expected energy savings within a two-year period
Source: own elaboration

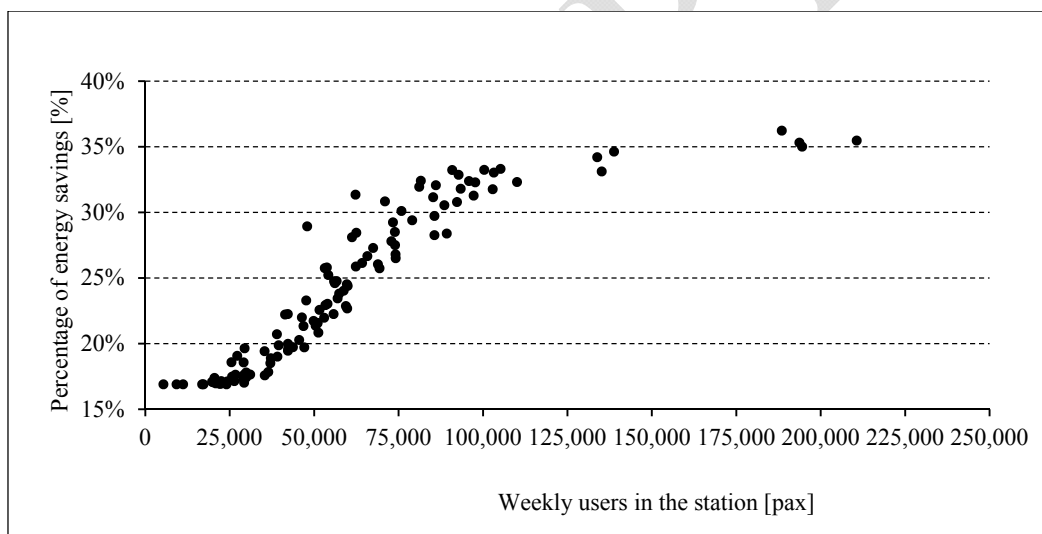


Figure 16. Percentage of energy savings achieved with the suggested dimming strategy in the stations of the Barcelona metro network, depending on the number of weekly users
Source: own elaboration

An analysis of the results at station level allows us to conclude that monthly energy savings are highly dependent on the month in the maintenance and cleaning cycle (Figure 17). As expected, savings were greater at the start of the maintenance period and just after luminaire cleaning. Most savings occurred when the station was open.

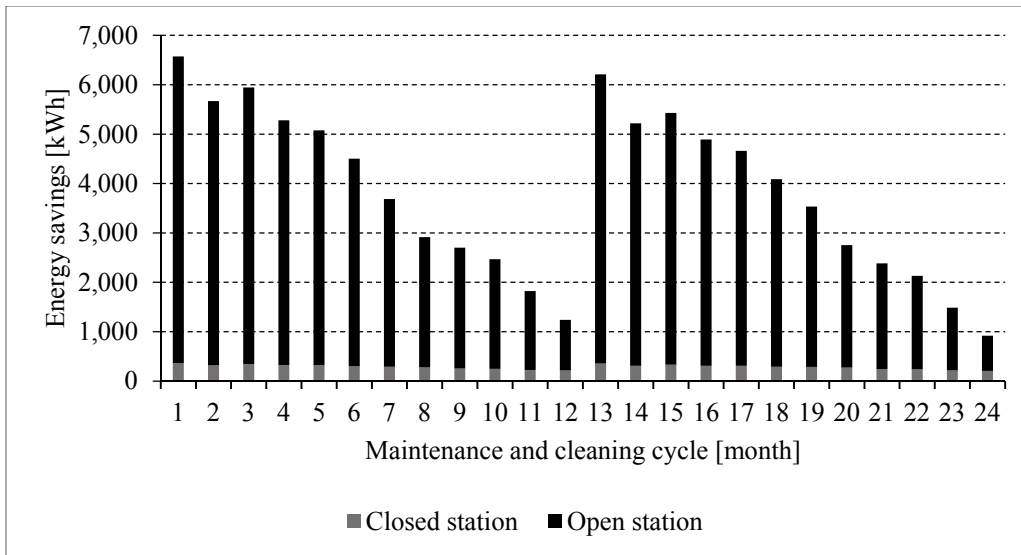


Figure 17. Energy savings profile in one of the underground stations of the Barcelona metro network, assuming that the maintenance cycle starts in January
Source: own elaboration

Energy savings derived from the application of dimming strategies are highly influenced by the extension of the maintenance and cleaning intervals. Moreover, the results also depend on the values adopted for both the maintenance factor (MF) and the comfort factor (CF). A low maintenance factor represents a high difference between the installed lighting power and the regulation requirements. In contrast, a high maintenance factor promotes energy efficient design and limits the installed lighting power requirement. In this case, dimming becomes less attractive. However, this option implies higher maintenance tasks, and therefore higher related costs. The comfort factor plays a similar role. Higher comfort factors involve greater differences between the actual lighting output and the regulation requirements. Therefore, higher comfort factors provide higher energy saving possibilities. Finally, the results also depend on the thresholds used as triggers for the dimming control. Dimming is allowed sooner and more frequently the smaller these values. In this case, energy savings due to comfort also increase.

5. CONCLUSIONS

The major contribution of this research is the development of a lighting energy saving strategy for underground stations using data mining techniques that does not require a high initial investment and can interoperate with existing technologies. An adaptive lighting system adjusts the lighting output according to the preventive maintenance and cleaning cycles of the luminaires and the station's occupancy. The electricity consumed to overcome the accumulation of dirt and aging of equipment is kept at a minimum by dimming the illuminance level throughout the lamp's lifespan, whilst always ensuring that the minimum legal requirements are met. In this case, the dimming level is higher at the beginning of the maintenance period, and just after the luminaire has been cleaned. The electricity consumed to enhance passengers' sense of security is also kept

at a minimum by dimming the illuminance level according to the expected number of users inside the station. In this case, the dimming level is higher during rush hours, when the visual horizon of a travelling passenger is much shorter because of the crowd. The k-means clustering technique is used to define stations' monthly occupancy patterns. Occupancy patterns allow modelling of the behaviour of the dimming strategies in each underground station and accurately forecast the corresponding energy savings. The approach benefits from information about stations' occupancy stored in the metro operator's existing databases, which have been used up until now for train scheduling and staff management purposes only. Therefore, it is worth highlighting that this is the first time that a metro operator's data on station occupancy has been used for building management purposes.

The application of the approach to a case study metro network has shown very promising results for saving energy used for lighting purposes. Energy savings figures (up to 36.22% of the lighting baseline consumption in the Barcelona metro network) allow us to predict that the approach could contribute to the future energy efficiency project plans of worldwide metro operators. In addition and taking into account that the energy saving is achieved by dimming the installed lighting power, there is no extra implementation cost than the one needed for including a digital addressable lighting interface (DALI) controller to the existing lighting fixtures. The approach could also be adapted to other underground spaces used for car parking, administrative, commercial or leisure purposes.

Future steps include assessing the impact of higher resolutions of the occupancy database, which would provide finer control policies and probably higher energy savings. In addition, further research is needed to economically assess the feasibility of the suggested approach. However, although savings opportunities were found to be unequal throughout the network, low payback times are expected in all cases. In any case, the results of this economic analysis would help to prioritise interventions across the network.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Barcelona metro network operator (TMB, Transports Metropolitans de Barcelona) for providing the occupancy databases for their underground stations.

REFERENCES

- [1] Casals M, Gangoellés M, Forcada N, Macarulla M, Giretti A. A breakdown of energy consumption in underground stations. *Energy Buildings* 2014;78:89-97. <doi:10.1016/j.enbuild.2014.04.020>.
- [2] Shuguang L. An optimal model for tunnel lighting control systems. *Tunn Undergr Sp Technol* 2015;49:328–335. <doi:10.1016/j.tust.2015.05.001>.
- [3] Ye X, Xia X, Zhang L, Zhu B. Optimal maintenance planning for sustainable energy efficiency lighting retrofit projects by a control system approach. *Control Eng Pract* 2015;37:1–10. <doi:10.1016/j.conengprac.2014.12.014>.

- [4] Nagy Z, Yong FY, Frei M, Schlueter A. Occupant centered lighting control for comfort and energy efficient building operation. *Energ Buildings* 2015;94:100–108. <doi:10.1016/j.enbuild.2015.02.053>.
- [5] Khan I, Capozzoli A, Corgnati SP, Cerquitelli T. Fault detection analysis of building energy consumption using data mining techniques. *Energy Procedia* 2013;42:557–566. <doi:10.1016/j.egypro.2013.11.057>.
- [6] Knight IP. Measured energy savings due to photocell control of individual luminaires. *Light Res Technol* 1999;31:19–22. <doi:10.1177/096032719903100104>.
- [7] Fernandes LL, Lee ES, Dibartolomeo DL, McNeil A. Monitored lighting energy savings from dimmable lighting controls in the New York Times Headquarters Building. *Energ Buildings* 2014;68:498–514. <doi:10.1016/j.enbuild.2013.10.009>.
- [8] Van De Meughevel N, Pandharipande A, Caicedo D, Van Den Hof PPJ. Distributed lighting control with daylight and occupancy adaptation. *Energ Buildings* 2014;75:321–329. <doi:10.1016/j.enbuild.2014.02.016>.
- [9] Fathabadi H. Ultra high benefits system for electric energy saving and management of lighting energy in buildings. *Energ Convers Manage* 2014;80:543–549. <doi:10.1016/j.enconman.2014.01.002>.
- [10] Mahlia TMI, Razak HA, Nursahida MA. Life cycle cost analysis and payback period of lighting retrofit at the University of Malaya. *Renew Sustain Energy Re* 2011;15:1125–1132. <doi:10.1016/j.rser.2010.10.014>.
- [11] Tähkämö L, Halonen L. Life cycle assessment of road lighting luminaires – Comparison of light-emitting diode and high-pressure sodium technologies. *J Clean Prod* 2015;93:234–242. <doi:10.1016/j.jclepro.2015.01.025>.
- [12] Zhou X, Yan D, Ren X, Hong T. Data analysis and modeling of lighting energy use in large office buildings. *Ibpsa Org* 2015;86:275–287. <doi:10.1016/j.enbuild.2014.09.071>.
- [13] Cabrera DFM, Zareipour H. Data association mining for identifying lighting energy waste patterns in educational institutes. *Energ Buildings* 2013;62:210–216. <doi:10.1016/j.enbuild.2013.02.049>.
- [14] Aghemo C, Blaso L, Pellegrino A. Building automation and control systems: A case study to evaluate the energy and environmental performances of a lighting control system in offices. *Autom Constr* 2014;43:10–22. <doi:10.1016/j.autcon.2014.02.015>.
- [15] Haq MAU, Hassan MY, Abdullah H, Rahman HA, Abdullah MP, Hussin F, Said DM. A review on lighting control technologies in commercial buildings, their performance and affecting factors. *Renew Sustain Energy Rev* 2014;33:268–279. <doi:10.1016/j.rser.2014.01.090>.
- [16] Peruffo A, Pandharipande A, Caicedo D, Schenato L. Lighting control with distributed wireless sensing and actuation for daylight and occupancy adaptation. *Energ Buildings* 2015;97:13–20. <doi:10.1016/j.enbuild.2015.03.049>.
- [17] Yun GY, Kim H, Kim JT. Effects of occupancy and lighting use patterns on lighting energy consumption. *Energ Buildings* 2012;46:152–158. <doi:10.1016/j.enbuild.2011.10.034>.
- [18] Hong T, D’Oca S, Turner WJN, Taylor-Lange SC. An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs framework. *Build Environ* 2015;92:764–777. <doi:10.1016/j.buildenv.2015.02.019>.

- [19] Mahlia TMI, Said MFM, Masjuki HH, Tamjis MR. Cost-benefit analysis and emission reduction of lighting retrofits in residential sector. *Energ Buildings* 2005;37:573–578. <doi:10.1016/j.enbuild.2004.08.009>.
- [20] Jiang Y, Li S, Guan B, Zhao G. Cost effectiveness of new roadway lighting systems. *J Traffic Transp Eng (English edition)* 2015;2:158–166. <doi:10.1016/j.jtte.2015.03.004>.
- [21] Principi P, Fioretti R. A comparative life cycle assessment of luminaires for general lighting for the office - compact fluorescent (CFL) vs Light Emitting Diode (LED) - a case study. *J Clean Prod* 2014;83:96–107. <doi:10.1016/j.jclepro.2014.07.031>.
- [22] Huang BJ., Wu MS, Hsu PC, Chen JW, Chen KY. Development of high-performance solar LED lighting system. *Energ Convers Manage* 2010; 51:1669-1675. <doi:10.1016/j.enconman.2009.11.046>.
- [23] Chueco F, López F, Bobadilla M. Technical and economic evaluation of fluorescent and LED luminaires in underground mining. A case study: New mine level of El Teniente. *Energ Buildings* 2015;93:16–22. <doi:10.1016/j.enbuild.2015.02.022>.
- [24] Salata F, de Lieto Vollaro A, Ferraro A. An economic perspective on the reliability of lighting systems in building with highly efficient energy: A case study. *Energ Convers Manage* 2014;84:623-632. <doi:10.1016/j.enconman.2014.04.063>.
- [25] Ye X, Xia X, Zhang L, Zhu B. Optimal maintenance planning for sustainable energy efficiency lighting retrofit projects by a control system approach. *Control Engineering Practice* 2015;37:1–10. <doi:10.1016/j.conengprac.2014.12.014>.
- [26] SEAM4US. Sustainable Energy Management for Underground Stations. EU funded project. Contract number: contract no. 285408, 2011.
- [27] Vahl FP, Campos LMS, Casarotto Filho N., Sustainability constraints in techno-economic analysis of general lighting retrofits. *Energ Buildings* 2013;67:500–507. <doi:10.1016/j.enbuild.2013.08.039>.
- [28] European Committee for Standardization. EN 12464-1:2011 Light and lighting - Lighting of work places - Part 1: Indoor work places, Brussels; 2011.
- [29] Spain. Technical Building Code, Madrid; 2013.
- [30] Spain. Royal Decree 1544/2007 regulating the basic conditions of accessibility and no discrimination for accessing and using transport means for disabled people, Madrid; 2007.
- [31] International Commission on Illumination. CIE 97:2005 Guide on the maintenance of indoor electric lighting systems, Vienna; 2005.
- [32] Casals M, Gangolells M, Forcada N, Macarulla M, Giretti A. Energy performance assessment of an intelligent energy management system. *Renew Sustain Energy Re* 2016;55:662-667. <doi:10.1016/j.rser.2015.11.006>.
- [33] Arthur D, Vassilvitskii S. K-means++: The advantages of careful seeding. *Proc Eighteenth Annu ACM-SIAM Symp Discret Algorithms* 2007;8:1027–1035. <doi:10.1145/1283383.1283494>.
- [34] Baarsch J, Celebi ME. Investigation of internal validity measures for K-means clustering. *Proc Int MultiConference Eng Comput Sci* 2012; vol I, Hong Kong; 2012.
- [35] Zhao Q, Xu M, Fränti P. Sum-of-squares based cluster validity index and significance analysis. *Lect Notes Comput Sci* 2009;5495:313–322. <doi:10.1007/978-3-642-04921-7_32>. DAMA - UK, The six primary dimensions for data quality assessment, 2013.