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The lighting of housing estate parking spaces as a source of light pollution

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Abstract

This publication is devoted to the problem of lighting in parking spaces in a housing estate. Both aspects related to the safety of their users and the potential impact on the natural environment through the phenomenon of light pollution are discussed. Parking spaces are classified in terms of their purpose and lighting. It was found that half of them are insufficiently illuminated, often by light sources originally intended to illuminate green areas or streets. As a result, the illuminance of their surface is much lower than the value specified by standards for this type of public space. It was found that this form of outdoor lighting does not directly make a noticeable contribution to the artificial sky glow, which is the main form of light pollution. However, isolated cases of excessive lighting in parking spaces have been recorded. In this case, the light reflected from the pavement or the street makes a significant contribution to artificial sky glow. It is suggested to replace the lighting in parking spaces with dedicated sets of LED or MH luminaires, which would minimise the impact of this lighting on the environment while ensuring the proper lighting of both the surface and the vehicles parked on them.

Keywords: lighting, luminaires, parking areas, light pollution, safety

1. Introduction

Residential housing estates are an integral part of modern cities. The estate infrastructure consists not only of multi-family residential buildings but also includes streets, public facilities (such as shops, schools and kindergartens), as well as parking spaces. Among the latter, we can distinguish the estate parking areas, which are contemporary to the housing estate and form its integral part, as well as parking areas located next to residential buildings or public facilities such as shops, schools and kindergartens. With the development of motorisation, the number of such parking spaces has become insufficient, leading to the creation of a series of parking spaces along inner streets within the estates. In recent years, even these have become inadequate, resulting in the emergence of “wild” parking areas, occupying parts of green spaces or the backs of emerging service points.

Proper lighting is a crucial element of any parking area. Its correctness not only ensures the smooth functioning of the parking areas but also ensures the safety of its users. The lighting should facilitate surveillance of vehicles parked in the area by providing sufficient illumination and also prevent glare for both parking area users and external observers.

The outdoor lighting standard that applies to parking areas is strictly defined. It is part of a series of guidelines concerning proper lighting for both external and internal areas. Among the outdoor lighting standards, the following can be found: EN 12464-1:2011, EN 12464-2:2014, EN 15193:2008, DIN V 18599:2007, CIE 97:2005, CIE 154:2003[1] (SMD-LED, 2023). These standards refer to European norms and provide several guidelines that parking area lighting should follow. These include requirements for the Colour Rendering Index (CRI), Glare Rating (GR), and other parameters. However, the most important among them is the minimum allowable illuminance in the parking area and its uniformity. It is these guidelines that determine how much light a specific type of parking area needs.

Based on outdoor lighting standards, the required illumination for a parking area depends on the traffic intensity within it. Due to the traffic intensity and the associated minimum lighting requirements, three primary types of parking area are defined (PN-EN 12464-2, 2023):

- Parking with low traffic intensity: this typically refers to small parking areas near shops, residential buildings, townhouses, bicycle paths, etc. Due to the low traffic on these areas, the recommended illuminance level should be at least 5 lx (the same requirement applies to pedestrian paths).
- Parking with medium traffic intensity: these are often parking areas near supermarkets, office buildings, factories, sports complexes, etc. Due to the higher number of vehicles moving in these areas, the standard requires a higher illuminance level of 10 lx.
- Parking with high traffic intensity: these are parking areas located near shopping centres, large sports facilities, schools, or churches. The standard specifies a minimum illuminance level of at least 20 lx for these areas.

Additionally, lighting in parking areas should not be intrusive to the surroundings, meaning it should not contribute to light pollution. Specifically, it should not illuminate adjacent areas, especially the windows of nearby buildings (known as the trespass effect), and it should not cause glare that can blind drivers and pedestrians. Improper luminaire design can also contribute to the sky glow generated by the city’s artificial outdoor lighting (Walker, 1977; Brons et al., 2008; Ściężor, 2012; Guanglei et al., 2019; Ściężor, 2019; Helbich et al., 2020; Zielińska-Dąbkowska et al., 2020; Pothukuchi, 2021).

[1] The last two mentioned are technical reports of the International Commission on Illumination.

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Thus far, research has focused on the impact of artificial outdoor lighting on the environment in various contexts, such as the lighting of historic buildings (Fila et al., 2014; Kobav et al., 2021), office complexes (Parkins et al., 2015; Du et al., 2018; Kobav et al., 2021; Ścieżor & Czaplicka, 2022), and large-scale parking areas in shopping centres (Ścieżor & Czaplicka, 2023). The issue of the lighting of residential areas, which constitute a significant part of the city's area (about 10% in the case of Kraków within its administrative boundaries), is also important. These residential areas are typically located on the outskirts of the city and primarily serve as "bedroom communities" where residents spend their evenings and nights. Lighting pedestrian paths and mixed-use paths within such residential areas, using the example of the Podwawelskie estate in Kraków, has already been the subject of research (Ścieżor, 2022). During these studies, it was found that some of the residential parking areas and streets, the verges of which are also used for parking purposes, have a significant impact on the increase in light pollution levels, particularly on the brightness of the artificial sky glow. While newly designed residential areas tend to have underground parking, older developments like the Podwawelskie estate face challenges in providing adequate lighting for surface parking areas.

2. The research area.

The chosen research subject is the Podwawelskie estate (PE) in Kraków, which is part of the Dębniki district (District VIII). This estate is located on the western side of the Vistula River, near the historical centre of Kraków. It has a rectangular shape, bordered by the following streets: Konopnicka to the east, Dworska and Wierzbova to the north, Kapelanka to the west, and the river valley of Wilga to the south (Fig. 1).

Fig. 1. A schematic map of Kraków within its administrative borders with the division into districts shown. The Dębniki district (grey) and the Podwawelskie estate (red) are highlighted (own elaboration)

The complex of the Podwawelskie estate was established through an architectural competition held in 1965. The winning project was the "park-estate" concept prepared by the team led by Prof. Witold Cęckiewicz. The urban layout of the estate consists of long, four-story residential blocks with south-facing facades, arranged in parallel rows. There are four rows in total (5.16 Podwawelskie, 2022; Cęckiewicz, 2015: 172-173). The housing complex also includes sixteen ten-story tower blocks, which were freely placed amidst greenery on the western, southern and eastern edges of the estate (Cęckiewicz, 2015: 172-173). Several commercial and service pavilions complement the overall complex. The development of the PE urban complex took place between 1967 and 1976 (5.16 Podwawelskie, 2022). The total area of the PE is approximately 421 000 square meters, which represents 0.1% of the city's total area. Out of this, green areas cover around 185 000 square meters, accounting for a significant 44% of the analysed area.

On the attached map, all forty-seven parking spaces in the PE are marked, which are included in the Open Street Map (OSM) data (Fig. 2, subsequent references will be made to this map). Additionally, three local parking areas are marked, which are not present in the OSM data but are properly signposted on-site. As part of the estate planning, in the nineteen-sixties, a series of large local parking areas were designed along the western border of the estate, along Kapelanka street. These include a large open surface parking area (K2), south of which there are multi-level above-ground covered garages (PK), and further south, another open surface parking area (SW7). Parking areas were also designed near the school and the commercial-cultural pavilion (KW6), near the commercial pavilion (KW6), and in rows between residential blocks (SW..., SE..., KW..., KE...). In later years, with the construction of new residential blocks, a church and an increase in the number of residents, new parking areas were created (K1, SW7, KW9), and parking spaces were established along the residential streets (S..., SZ..., D...). Originally, the planned parking areas were to be illuminated either by neighbouring street luminaires (e.g. SW7) or by luminaires mounted along adjacent pedestrian paths (SW..., SE..., KW..., KE...). Over time, this lighting was supplemented with additional luminaires installed either on poles (BW2) or on the facades of buildings (SW..., SE..., KW..., KE...). However, some parking areas remain unlit (SW8, KW4).

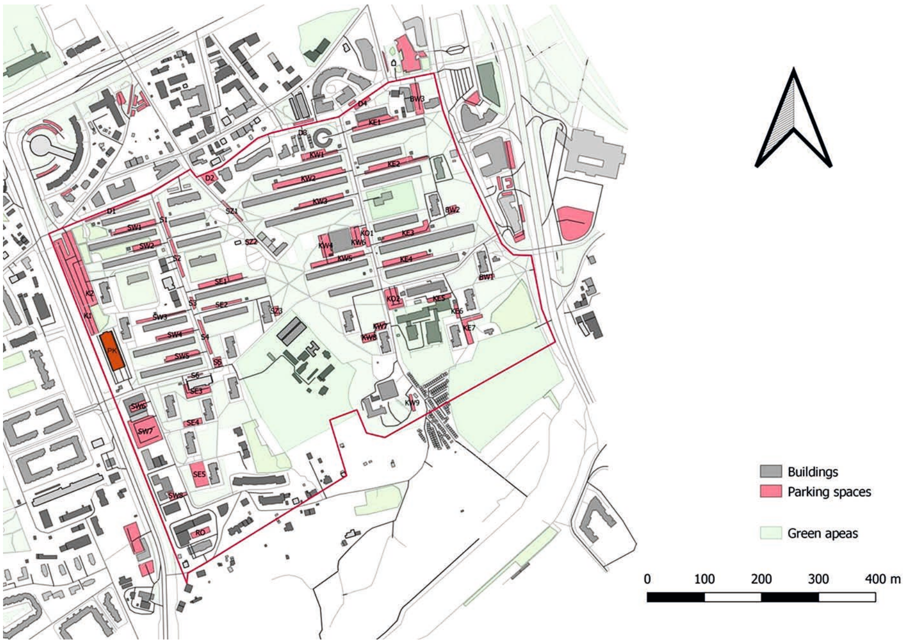

Fig. 2. Map of the Podwawelskie estate with marked parking spaces (own elaboration)

As part of this research, the lighting of parking spaces located within all parking areas in the area of the Podwawelskie estate was analysed.

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3. Parking spaces in the Podwawelskie estate and their lighting

3.1. Types of luminaires used for parking area lighting in the Podwawelskie estate

The following types of light sources were found in the luminaires used for illuminating parking spaces in the Podwawelskie estate:

- High-Pressure Sodium lamps (HPS): these light sources produce light with a Correlated Colour Temperature (CCT) of 2000 K, perceived as yellow-golden or orange, as a result of the discharge in an environment of sodium vapour under the pressure of approximately 2 Pa. Their luminous efficacy ranges from 80 to 150 lm/W. They are available in nominal power ratings ranging from 50 to 1000 W (for outdoor lighting: to 200 W), and depending on their construction, their lifespan is between 10 000 and 24 000 hours. Due to their colour rendering index (CRI), they have a wider range of applications compared to low-pressure luminaires. HPS luminaires enhance visual acuity in dust and fog, making them suitable for illuminating roadways, factory premises, and open areas (Bąk, 1981, Wiśniewski, 2013).

  In the Podwawelskie estate, HPS luminaires used for parking area lighting are mounted on freestanding poles and can be found in the following forms:
  - freestanding globe-shaped park luminaires, installed on 6-metre poles (B_{HPS}), illuminating pedestrian paths and adjacent parking spaces (Fig. 3a);
  - freestanding street luminaires (U_{HPS}), installed at right angles on 9-m or 10-m poles, illuminating internal roads and some parking areas within the housing estate (Fig. 3b).
- LED lamps: these light sources utilise white light-emitting diodes (LEDs) as the light source. Typically, these LEDs consist of a blue LED and a phosphor. The phosphor emits yellow-green light, which, when combined with the blue light from the LED, creates white light. Depending on the type of phosphor, various colour temperatures of white light can be achieved. The primary advantages of LED luminaires include their high durability (over 50 000 hours), high efficiency, ability to produce different colours of light without using coloured filters, low operating costs, and the absence of harmful ultraviolet (UV) radiation, which is detrimental to human eyesight, skin and artworks. The luminous efficacy of LED luminaires ranges from 70 to 180 lm/W (and can reach up to 300 lm/W). Another benefit is their high colour rendering index. However, it was noted that all LED luminaires in the analysed area have a high CCT, which can harm humans and other living organisms (Tähkämö et al., 2019).

  In the Podwawelskie estate, LED luminaires used for illuminating parking spaces are found in three forms:
  - Wall-mounted luminaires with flat lampshade (E_{LED-E}): these luminaires are installed on the walls of buildings at a semi-right angle, usually above building entrances, at a height of 5 m. They are located along pedestrian paths and in the parking areas between residential blocks (detailed description: Ścieżor, 2022) (Fig. 3c).
  - Freestanding street luminaires with flat lampshade (U_{LED}): these luminaires are mounted at right angles on 9- or 10-m poles (Fig. 3d).
  - Directional spotlights (floodlights) (R_{LED}): these luminaires are mounted on building facades at various heights and at various angles.

It should be noted that the B_{HPS} globe-shaped luminaires, installed during the construction of the housing estate in the nineteen-seventies, exhibit a high degree of degradation. Both the spherical lampshades (particularly their upper

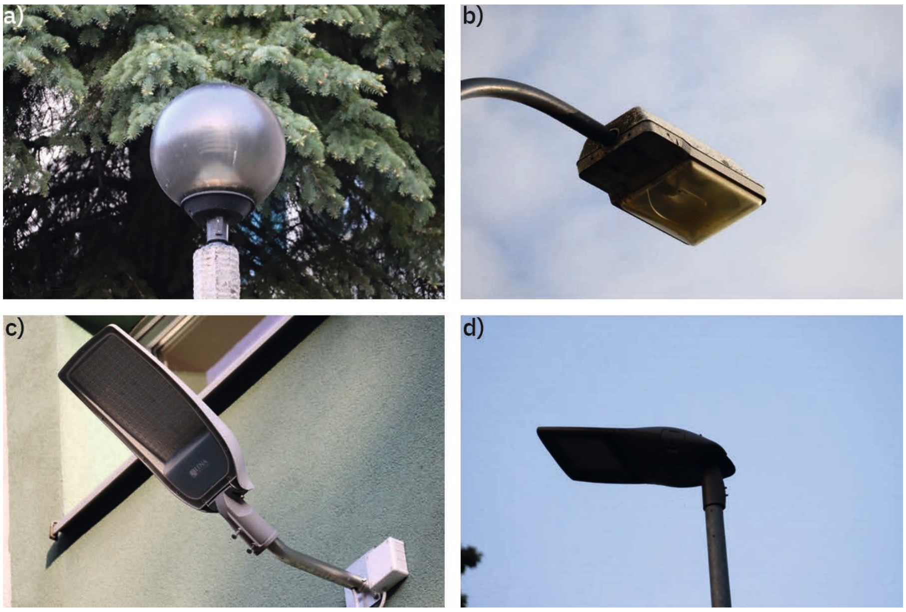

Fig. 3. Some examples of outdoor luminaires used to illuminate parking spaces in the Podwawelskie estate in Kraków: B_{HPS} (a), U_{HPS} (b), E_{LED-E} (c) and U_{LED} (d) (own elaboration)

parts, exposed to weather conditions and biological damage) and the light sources themselves (HPS lamps) have deteriorated. Regardless of the conducted measurements, the visual assessment of these luminaires is negative – they do not adequately illuminate the designated areas and they create an impression of darkness. Furthermore, they were placed in locations originally intended as the estate's park areas, often standing among trees, in the middle of lawns, or hidden within the tree canopies (e.g. parking SE5, Fig. 2). The U_{HPS} luminaires, intended for illuminating internal streets, are not suitable for illuminating parking spaces located on the opposite side of the street (e.g. S6 or SW7). On the other hand, both LED luminaires, E_{LED-E} and U_{LED}, provide proper illumination for parking spaces, especially when they have been specifically designed for this purpose (e.g. parking BW3). A detailed analysis of the lighting of parking spaces in each of the investigated cases is the subject of this study.

3.2. Inventory of parking spaces in the Podwawelskie estate

During the inventory of lighting in the parking spaces of the Podwawelskie estate, the following types of luminaires (the abbreviations used in the study are given in brackets) were identified:

- Elektrim OCP-70 KP-PC 1×WLS 70 W, HPS (OCP);
- ES-System RACER MINI VMC, LED (RACER);
- GTV NAŚWIETLACZ LED IP65 50W 4000lm 6400K, LED (GTV);
- LED-SCHREDER AMPERA MIDI 5121 139W, LED (AMPERA);
- Ledvance Floodlight Naświetlacz LED 50W 6000lm 4000K IP65, LED (Ledv);
- LENA Led Corona Basic 2 54W 5700Lm 840 Ip66 I Kl, LED (LENA);
- Siemens 5NA 550 2-7S-P 1×NAV T 100 W, HPS (5NA-100);
- Siemens 5NA 550 2-1S-P 1×NAV T 150 W, HPS (5NA-150).

The following table (Table 1) provides a summary of all the examined parking spaces in the area of the PE, along with a description of their lighting.

Table 1. List of parking spaces in the Podwawelskie estate, Kraków. Parking spaces outside the OSM database are marked in grey. The symbols for the location of the luminaires are as follows: E – on the neighbouring building facade, D – in a wooded area, P – on the edge of the parking space (indicated cardinal direction: N, E, S, W), U(P) – along the street, on the parking side, U(D) – along the street, on the opposite side.

No.	Code	Area [m²]	Parking location	Light source	Luminaire location	Luminaire type/height [m]
1	BW1	173	In front of the residential block entrance	E_{LED-E}	E	LENA/5
2	BW2	221	In front of the residential block	E_{LED-E}	E	LENA/5
3	BW3	781	Along the facades of the tenement houses on Na Ustroniu Street	U_{LED}	U(P)	RACER/10
4	D1	252	Along the southern side of Dworska Street	U_{HPS}	U(P)	5NA-150/10
5	D2	416	Closed company parking	U_{HPS}	U(D)	OCP/10
6	D3	35	Next to a small service complex	No lighting	No lighting	No lighting
7	D4	154	In front of the commercial-service pavilion	U_{LED}	U(P)	AMPERA/9
8	K1	3721	Along the western boundary of the PE[1]	No lighting	No lighting	No lighting
9	K2	1401	Along the western boundary of the PE	U_{HPS}	P(E)	5NA-100/10
10	KE1	971	Between the back of the commercial-service pavilion and the residential block	E_{LED-E}	E	LENA/5
11	KE2	1077	Between residential blocks[2]	E_{LED-E}	E	LENA/5
12	KE3	1022	Between residential blocks[3]	E_{LED-E}	E	LENA/5
13	KE4	951	Between residential blocks	E_{LED-E}	E	LENA/5
14	KE5	309	Back of the commercial-service pavilion, in front of the school entrance[4]	B_{HPS}	D	OCP/6
15	KE6	160	Along the street near the school	B_{HPS}	D	OCP/6
16	KE7	608	Along the facades of two residential blocks	E_{LED-E}	E	LENA/5
17	KO1	267	Along the western side of Komandosów Street	U_{HPS}	U(D)	AMPERA/9
18	KO2	883	In front of the school and the commercial-service pavilion	U_{HPS}	U(D)	AMPERA/9
19	KW1	662	Along the facade of a residential block	E_{LED-E}	E	LENA/5
20	KW2	1397	Between residential blocks	E_{LED-E}	E	LENA/5
21	KW3	725	Between residential blocks	E_{LED-E}	E	LENA/5
22	KW4	718	Back of the supermarket[5]	No lighting	No lighting	No lighting
23	KW5	878	Along the facade of a residential block	E_{LED-E}	E	LENA/5
24	KW6	563	In front of the supermarket	U_{HPS}	U(D)	AMPERA/9
25	KW7	232	By the northern facade of a residential block	E_{LED-E}	E	LENA/5
26	KW8	369	By the western facade of a residential block	E_{LED-E}	E	LENA/5
27	KW9	147	By the church[6]	No lighting	No lighting	No lighting
28	RO	342	Courtyard between blocks	R_{LED}	E	Ledv/2
29	S1	317	Along the eastern side of Słomiana Street	U_{HPS}	U(D)	5NA-100/10
30	S2	332	Along the eastern side of Słomiana Street	U_{HPS}	U(D)	5NA-100/10
31	S3	104	Along the eastern side of Słomiana Street	U_{HPS}	U(D)	5NA-100/10
32	S4	304	Along the eastern side of Słomiana Street	U_{HPS}	U(D)	5NA-100/10
33	S5	234	Along the eastern side of Słomiana Street	U_{HPS}	U(D)	5NA-100/10
34	S6	61	In front of a commercial and service pavilion	U_{HPS}	U(D)	5NA-100
35	SE1	820	Between residential blocks	E_{LED-E}	E	LENA/5
36	SE2	305	Between residential blocks	E_{LED-E}	E	LENA/5
37	SE3	696	The backyard of a commercial and service pavilion[7]	B_{HPS}	P(S)	OCP/6
38	SE4	322	Along a side street between blocks	B_{HPS}	U(D)	OCP/6
39	SE5	1031	Among trees at the eastern edge of the parking area[8]	B_{HPS}	D	OCP/6
40	SW1	771	Between residential blocks	E_{LED-E}	E	LENA/5

No.	Code	Area [m²]	Parking location	Light source	Luminaire location	Luminaire type/height [m]
41	SW2	548	Between residential blocks	E_{LED-E}	E	LENA/5
42	SW3	398	Between residential blocks	E_{LED-E}	E	LENA/5
43	SW4	559	Between residential blocks	E_{LED-E}	E	LENA/5
44	SW5	603	Between residential blocks	E_{LED-E}	E	LENA/5
45	SW6	353	Closed, on the premises of a service company	R_{LED}	E	GTV/7
46	SW7	2243	Along the western border of the PE, on the other side of Słomiana Street	U_{HPS}	U(D)	5NA-100/
47	SW8	273	The backyard of a commercial and service pavilion	No lighting	No lighting	No lighting
48	SZ1	262	Along the western side of Szwedzka Street	U_{HPS}	U(P)	5NA-150/10
49	SZ2	164	In front of a kindergarten building	No lighting	No lighting	No lighting
50	SZ3	146	At the facade of a residential block	E_{LED-E}	E	LENA/5.

Notes:
[1] The northern part is illuminated by freestanding HPS luminaires (P(E)).
[2] One additional B_{HPS} luminaire.
[3] In each case, E_{LED-E} luminaires are placed at large intervals, usually three per entire facade (approximately every 20–30 m).
[4] In the western part, there is an additional LED luminaire (E).
[5] The only source of light is the illumination of the rear technical entrance to the building (fluorescent luminaire).
[6] The only source of light is a distant street luminaire from the north (U(P), HPS).
[7] Lighting above the rear technical entrances to the building (LED).
[8] Additionally, among the trees on the northern side of the parking area, there are single B_{HPS} luminaires.

4. Used units

In the paper, the following units were used, as previously described in detail (Ścieżor, 2022): for radiance (L) determined based on VIIRS/DNB satellite data, the unit is $W·m^{-2}·sr^{-1}$ (watts per square metre per steradian), and its derived unit is $nW·m^{-2}·sr^{-1}$ (nanowatts per square metre per steradian). For illuminance of the ground (E), the unit used is lux (lx). The surface brightness of the night sky is given in astronomical units of magnitude per square arcsecond ($mag·arcsec^{-2}$), and correlated units of luminance such as millicandela per square metre ($mcd·m^{-2}$).

5. Measurement methodology

5.1. Remote sensing

To determine the total radiance from the study area, nighttime images were used in the DNB (Day Night Band) spectral range captured by the VIIRS camera mounted on the Suomi National Polar-orbiting Partnership (SNPP) satellite (Elvidge et al., 2013; Wolfe et al., 2013).

In addition, high-resolution images obtained from the International Space Station (ISS) were also utilised. The comparison between the VIIRS/DNB images and the night photograph of Kraków taken from the ISS in 2017 (Zamorano et al., 2011; Sánchez de Miguel et al., 2019; Gateway to Astronaut Photography of Earth, 2021), in which the size of a single pixel is 13.5 × 13.5 m, enables the identification of the main light sources in the study area.

5.2. Measurements of illuminance

For the measurement of illuminance of the ground, a Sonopan P-200 control panel equipped with a highly sensitive L-200 photometric sensor was used, with a resolution in the lower range of 0.001 lx. The measurements were performed at ground level, with the photometric head of the luxmeter directed towards the zenith. Illuminance was measured at a minimum of five points, evenly distributed across the parking area. For larger parking areas (e.g., K1, K2, S1, S4), the number of measurement points was increased to several dozen, ensuring that the distance between them did not exceed 5 m. In each measurement case, care was taken to position the measurement points in such a way that neither the measurer nor parked vehicles cast shadows on the photometric head of the luxmeter. Following these principles, a total of 353 illuminance measurements were conducted.

To minimise the effect of background brightening caused by city lights reflecting off clouds, the measurements were taken under clear sky and moonless conditions. Additional verification measurements were conducted under a partially cloudy and moonless sky, and it was determined that such cloud cover increases the ground illuminance by only about 0.1 lx.

5.3. Spectral analysis

The identification of light source types in the luminaires was done using diffraction gratings from AstroMedia (Article No. 407.NDI) with a constant grid of 1000 lines/mm (Zamorano, 2020).

5.4. Equidensitometry

Due to the unavailability of a luminance camera to determine the luminance distribution of parking areas, the equidensitometry method was used for this purpose. This method consists of image analysis that involves replacing the image with an image created from lines running through points of equal optical density (equidensities) (Brown, 2010). For this purpose, photographs of some parking areas (RO, SW8, SE5, SW7) taken from the upper floors of nearby residential blocks were used.

6. Measurements results

6.1. Remote sensing

Based on the analysis of the calibrated ISS photograph, it can be concluded that the bright areas visible in it are either associated with the lighting of the streets and parking areas located along the streets, or with illuminated parking spaces (Fig. 4). Field reconnaissance confirmed that in none of the cases is it direct light emitted by the luminaires illuminating these objects but rather light reflected from the bright surfaces of the streets, sidewalks, and parking areas. The main sources of radiance can be identified as areas D1, S1-S5, D2 (inactive during the study), KW6, KW7 and KE7.

6.2. Measurements of the brightness of the sky glow

The analysis utilised measurements of the surface brightness of the night sky (S_a) taken in 2000 during the nighttime outdoor lighting reductions related to the COVID-19 lockdown (Ściężor, 2021). It was observed that under clear and moonless skies, the zenithal value of S_a increased from 18.6 mag·arcsec^{-2} with full lighting on to 19.1 mag·arcsec^{-2} with street and parking lighting turned off. This corresponds to a decrease in luminance from the initial 4.1 mcd·m^{-2} to 2.5 mcd·m^{-2} (Crawford, 1997).

In the case of a completely overcast sky with low-level *Stratus* clouds, the respective values of S_a (and their corresponding luminance) were 15.5 mag·arcsec^{-2} (68.7 mcd·m^{-2}) and 16.2 mag·arcsec^{-2} (36.1 mcd·m^{-2}).

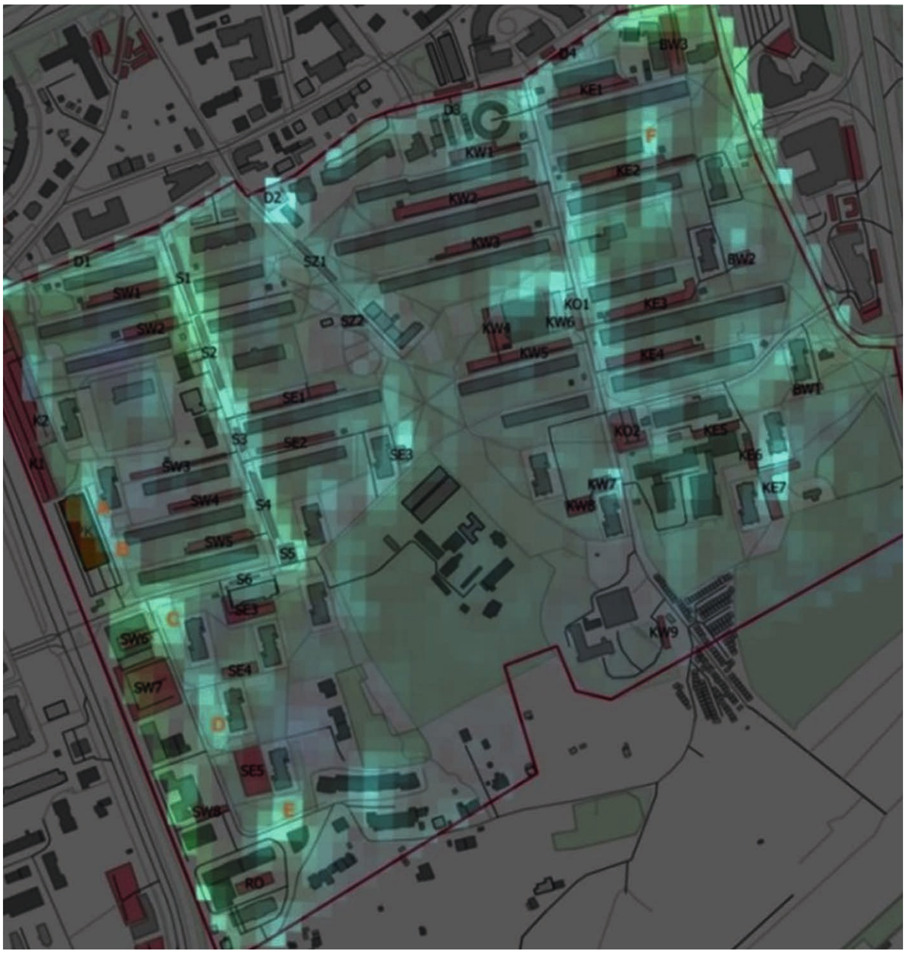

Fig. 4. Map of the Podwawelskie estate in Kraków overlaid on a satellite image of the area taken from the ISS in 2017. Bright areas correspond to parking areas (black text) and the lighting of approaches to residential blocks (orange text) (own elaboration)

6.3. Measurements of illuminance

For the area not illuminated by artificial light in the PE (parking KW9, where the lighting was not functioning during the study), measurements of ground illuminance were performed. In the case of a clear sky, a value of 0.11 lx was obtained, while for a completely cloudy and moonless sky, it was 0.27 lx. These values should be considered as the urban background for the analysed area.

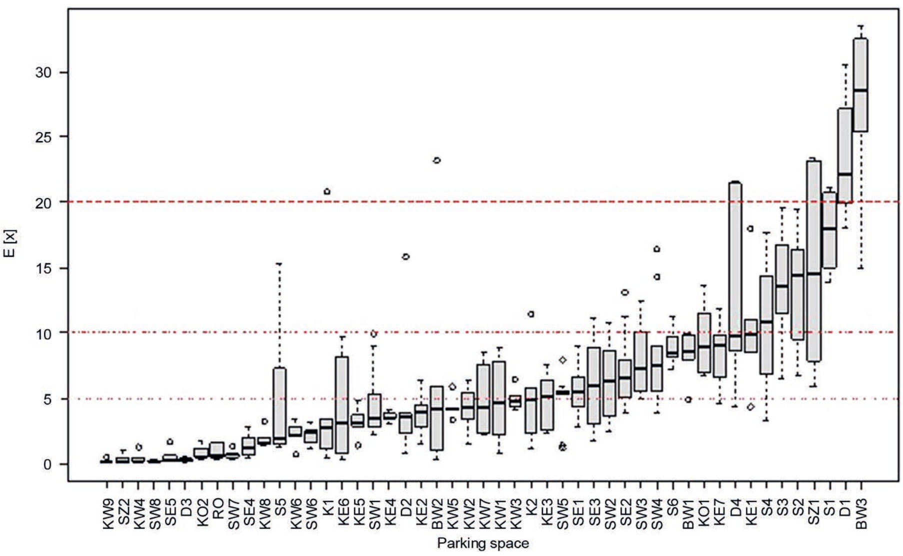

Fig. 5. Distributions of illuminance in the parking spaces of the Podwawelskie estate arranged in ascending order of medians (horizontal lines). The heights of the boxes represent the widths of the distributions (interquartile ranges), while the dashed vertical lines indicate the ranges between the minimum and maximum measured illuminance values. The dashed horizontal lines represent the minimum allowable illuminance according to the standards for parking areas with low (dotted line), medium (dashed-dotted line) and high (dashed line) traffic intensity (own elaboration)

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A total of 353 measurements of ground illuminance were conducted within all parking areas in the Podwawelskie estate. Due to the uneven distribution of lighting in the parking areas and occasional isolated points with significantly higher illuminance values, the median value (Me) was considered to be a better representation of the average value than the arithmetic mean (Av). For the same reasons, interquartile ranges (RQ) were used to determine the variation of the measured quantity in these areas (Table 2, Fig. 5).

Table 2. Measures of central tendency (medians, Me), average (arithmetic means, Av) and variability (interquartile ranges, RQ) of the ground illuminance calculated for the studied parking spaces (PS) in the Podwawelskie estate

PS	Av [lx]	Me [lx]	RQ [lx]	PS	Av [lx]	Me [lx]	RQ [lx]
BW1	8.262	8.625	1.840	KW9	0.184	0.110	0.004
BW2	6.925	4.121	4.948	RO	0.908	0.536	1.145
BW3	26.958	28.54	7.13	S1	17.803	18	5
D1	23.594	22.11	7.30	S2	13.029	14.42	6.91
D2	5.266	3.591	1.517	S3	13.490	13.595	4.485
D3	0.322	0.361	0.1375	S4	10.988	11.88	7.49
D4	13.186	4.364	12.820	S5	5.164	1.926	5.696
K1	5.737	2.807	2.322	S6	8.907	8.765	1.292
K2	5.105	1.49	3.55	SE1	5.724	5.534	1.310
KE1	10.359	9.883	2.604	SE2	7.024	6.594	2.543
KE2	3.838	3.935	1.610	SE3	5.563	5.629	5.016
KE3	4.788	5.091	3.890	SE4	1.720	1.646	1.535
KE4	3.589	3.487	0.423	SE5	0.571	0.279	0.430
KE5	3.190	3.128	0.812	SW1	4.571	3.466	2.505
KE6	4.386	3.059	7.446	SW2	6.388	6.402	5.068
KE7	8.421	9.036	3.232	SW3	7.726	7.257	4.037
KO1	9.567	8.975	4.602	SW4	8.400	7.471	2.811
KO2	0.852	0.852	0.755	SW5	4.884	5.380	0.265
KW1	4.883	4.71	5.70	SW6	2.196	1.641	1.121
KW2	4.167	4.265	2.113	SW7	0.727	0.666	0.249
KW3	4.985	4.851	0.769	SW8	0.187	0.172	0.036
KW4	0.397	0.143	0.275	SZ1	14.973	14.59	15.31
KW5	4.361	4.168	0.164	SZ2	0.313	0.113	0.390
KW6	2.251	2.203	0.776				
KW7	4.968	4.32	5.27				
KW8	1.909	1.56	0.51				

To group the parking spaces in the PE based on their illuminances, a hierarchical clustering analysis was performed using Ward's minimum variance criterion (Ward's D2). As a result, a dendrogram was created, illustrating the hierarchy of clusters and the distances between them (Fig. 6).

Uneven ground illuminance was observed in the majority of the analysed parking areas. This applies to both inter-block parking spaces (Fig. 7a), those located along streets (Fig. 7b), and those near commercial and service points (Fig. 7c). Often, the lack of illumination in certain parts of the parking areas is caused by dense tree canopies obstructing the lighting of the parking spaces (Fig. 7d).

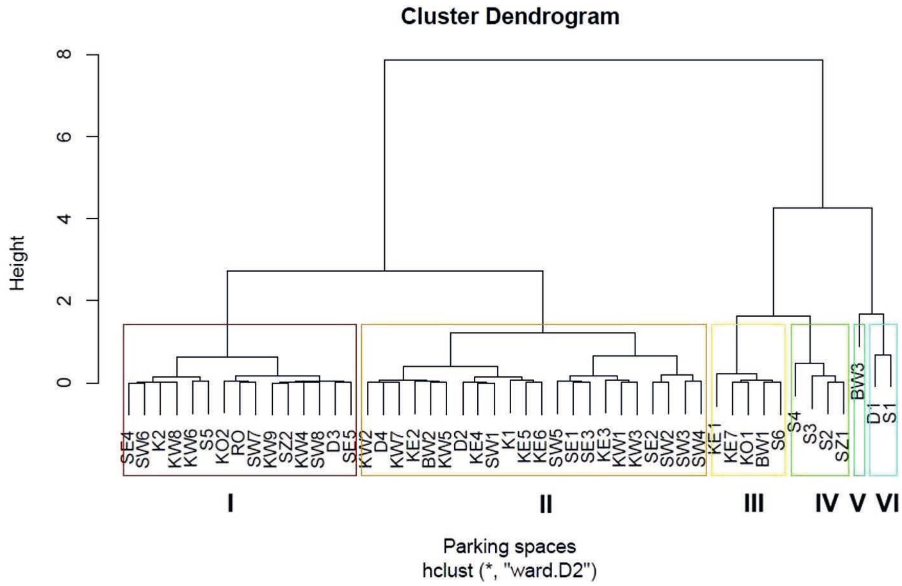

Fig. 6. Dendrogram showing the clustering of ground illuminances in all analysed parking areas within the Podwawelskie estate. Subsequent clusters are labelled with Roman numerals (own elaboration)

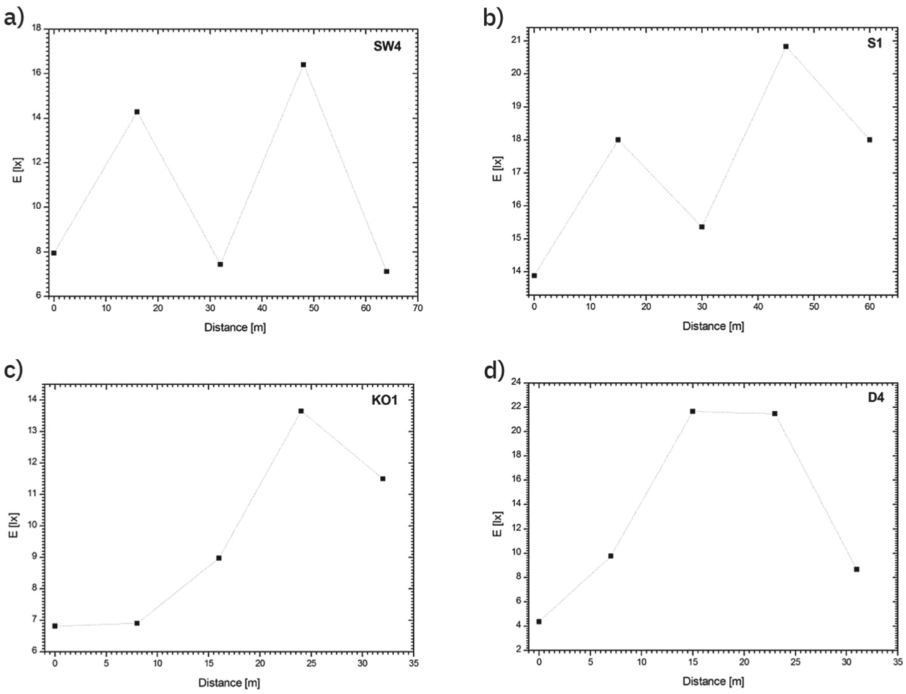

Fig. 7. Illuminance along several examples of parking areas in the PE: street parking (a), inter-block parking (b), in front of a supermarket (c), in front of a commercial and service pavilion (d). Distances are measured evenly along the entire parking length (own elaboration)

The measured maximum illuminance values in individual parking areas range from over 30 lx (BW3) to as low as approximately 0.03 lx (SZ2), which is equivalent to the illumination provided by the night sky glow in the studied area (Ścieżor, 2022). In several cases, under-illumination was observed either for the entire parking area (e.g. SZ2, SE5, KW6) or for certain parking spaces within an otherwise properly lit parking area (e.g. D4, S4).

6.4. Spectral analysis

The spectral analysis of all light sources illuminating the parking areas in the PE revealed that in 50% of cases (all E-type and some U-type light sources), the luminaires are based on light-emitting diodes (LEDs). The CCT of these luminaires is approximately 4500 K. Among the remaining light sources, 38% are yellow-glowing, high-pressure sodium (HPS) discharge lamps with a CCT of approximately 2000 K. In six cases (12%), either the parking area remained unlit (e.g. D3, SW8, SZ2), the lighting was turned off (KW6), or it was provided by street luminaires located outside the PE area (K1). In one case (KW4), the only light source is a single fluorescent luminaire illuminating the back entrance to the warehouse of a supermarket.

6.5. Equidensitometry

To determine the illuminance distribution of the analysed parking spaces, an equidensitometric analysis of photographs of them was performed. This was done only for a few cases in which it was possible to take photographs from the upper floors of buildings (RO, SE5, SW8, and SW7) (Fig. 8).

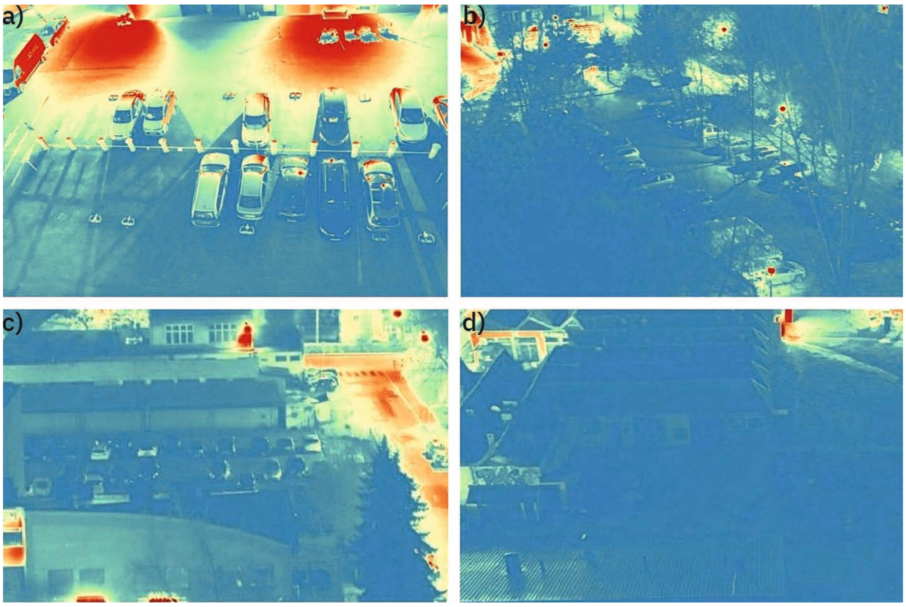

Fig. 8. Illuminance distribution (equidensitometric images) in selected parking areas in the Podwawelskie estate: (a) RO, (b) SE5, (c) SW7 and (d) SW8. Deep blue represents the lowest illuminance (0 arb. unit), while deep red represents the highest illuminance (255 arb. unit) (own elaboration)

7. Analysis of the results

The outdoor lighting of each area, especially parking spaces, must adhere to the principles of sustainable development: it should be both efficient and fulfil its function while minimising its impact on the environment.

7.1. Lighting of parking areas as a source of light pollution

As was previously stated, the lighting of the streets (along with the roadside parking areas) as well as surface parking areas are the main sources of radiance in the Podwawelskie estate, significantly contributing to the artificial sky glow of Kraków (Ściężor, 2022). In 2020, the shutdown of the lighting of streets and parking areas due to the COVID-19 pandemic resulted in a 53% reduction in radiance. Within the same study, it was observed that for clear skies, the shutdown of the lighting of streets and parking areas led to a 39% decrease in luminance, while for completely cloudy skies, the decrease was 47%. As demonstrated by Ściężor (2018), the brightness of the sky glow for clear skies is associated with the light emission from a large area on the Earth's surface (with a radius of approximately 20 km), whereas for low cloud cover this area is significantly smaller (around 1 km). This implies that the significant reduction in luminance in the first case is attributable to a considerable portion of Kraków, while in the second case, it is associated with an area close to the Podwawelskie estate. Therefore, it can be concluded that the lighting of parking areas in the PE significantly contributes to the brightness of Kraków's artificial sky glow.

The analysis of the satellite image of the Podwawelskie estate (Fig. 4) enables the identification of the main sources of radiance within its area, active in 2017. These include:

- the lighting along Słomiana Street and, to a lesser extent, Komandosów Street, which also illuminates the parking areas S1, S2, S3, and S4, as well as KO1 and KW6;
- the lighting of parking area D2;
- the lighting of parking area SE3;
- the lighting of parking area KW7;
- the lighting of parking area KE7.

Since 2017, there have been only minor changes in the lighting configuration in PE. The lighting of parking area D2 is currently turned off, while the lighting of parking area BW3 has been installed.

Upon analysing the reasons why the mentioned parking areas are the main sources of radiance, it has been determined that the primary factor responsible for this effect is the high light reflectance of the surface, specifically the bright paving used in the parking areas. In the case of parking areas SE3, KW7, and KE7, the light sources are LED facade lighting units with LENA luminaires installed on the facades of adjacent buildings. These luminaires, commonly installed in the PE area in the early twenty-first century, illuminate all the interblock parking spaces (e.g., SW1, SW2, SW3, SW4, KW3, KE3, etc.). However, directly beneath these luminaires, there are lawns and low-light-reflecting shrubs. In the case of parking areas SE3, KW7, and KE7, the paved area extends to the block walls, causing the light to significantly reflect upward. This effect is also observed in other locations where luminaires of this type are used to illuminate paved approaches to refuse rooms (Fig. 4: D) or building entrances (Fig. 4: A, B, C, E).

A similar effect applies to parking areas located along Słomiana Street and Komandosów Street. In this case, street luminaires with HPS (Słomiana Street) and LED light sources (Komandosów Street) primarily illuminate the streets themselves, as well as the parking areas situated on the opposite sides. Once again, the bright pavement of the streets becomes a source of radiance in this scenario.

Some of the analysed luminaires also generate light pollution in the form of glare and trespass. A typical example of glare is the lighting of the RO parking area. The Ledvance Floodlight LEDs mounted on the facade of the building at a height of 2 m above ground level are installed in a plane almost parallel to the wall of the building. As a result, they poorly fulfil their function of illuminating the parking area several metres away while causing glare for both pedestrians and drivers using the parking area.

The studied area also shows examples of the light trespass effect. Freestanding street luminaires with globe-shaped Elektrim OCP-70 HPS luminaires, commonly installed during the construction of the housing estate, poorly illuminate both the nearby ground and adjacent parking areas (e.g. SE5, KE5, KE6), but they illuminate the windows of neighbouring buildings. A similar effect occurs in the case of the BW3 parking area, where modern LED luminaires with ES-System RACER MINI VMC luminaires are mounted on tall poles placed close to the building's facade, causing a significant amount of light to illuminate the interiors of the adjacent apartments.

7.2. The efficiency of parking area lighting

In the analysed area, there are single parking areas illuminated by intentionally installed street luminaires (RO, K2, BW3, KW9[2]). In other cases, the function of lighting is fulfilled either by street luminaires with LED or HPS light sources, illuminating adjacent streets (e.g. SE1-SE4, SW7, KO1), or by secondary-mounted luminaires with LED lamps of the LENA Led Corona Basic 2 type on

[2] Turned off during research.

building facades (all interblock parking areas, SE3, KE6, KE7, ...). This is the most common reason for insufficient lighting in parking areas.

To distinguish between different groups of luminaires in terms of the illumination of parking areas, a clustering analysis using the Ward D2 hierarchical method was performed. To determine the optimal number of clusters, the elbow method was used, which indicated the presence of six such clusters:

- The first notable cluster is Cluster V, represented by the individual parking area BW3.
- Similar illuminances are observed in parking areas D1 and S1 (Cluster VI), as well as SZ1, S2, S3 and S4 (Cluster IV). In all these cases, these parking areas are located along residential streets, and the lighting is provided by street luminaires with HPS light sources. Similar luminaires form Cluster III.
- Cluster II primarily includes inter-block parking areas illuminated by LED luminaires of the LENA type.
- Cluster I consists of parking spaces that are either not illuminated at all (e.g. D3, K2, KW9) or illuminated by distant street luminaires (e.g. SW7), park luminaires (e.g. SE5) or improperly illuminated (e.g. RO).

Both the median illuminance for all parking spaces and the range of measured values are shown in the box plot (Fig. 5). The minimum illuminance values required by the PN-EN 12464-2:2014-05 standard are also indicated: 5 lx for parking areas with low traffic intensity (inter-block, near shops), 10 lx for parking areas with moderate traffic intensity (supermarkets, office buildings, workshops), and 20 lx for areas with high traffic intensity (shopping centres, schools, churches).

Nearly half of the analysed parking areas do not meet the minimum requirement of a 5 lx illuminance level for any parking space. Interestingly, the lowest value was found for parking KW9, located near a church, where a minimum of 20 lx is required[3]. Similarly, a low illuminance level is observed for parking SZ2, located near a preschool. This parking area lacks lighting, and the light from surrounding street luminaires is shielded by dense tree canopies surrounding the area. Another parking area without lighting is SW8, which is situated near an automotive workshop. In this case, the illumination from nearby street luminaires is obstructed by the building of the workshop (Fig. 8d). An interesting case is parking SE5, which was planned during the construction of the PE. Its illumination is provided by nearby HPS globe-shaped luminaires. Not only do these luminaires poorly illuminate the ground (Ścieżor, 2022), but their light also gets absorbed by the dense foliage of surrounding trees. This effect is also shown in the equidensitometric image of this parking area (Fig. 8b). Parking SE4 has a similar lighting condition.

The group of parking areas with the worst lighting also includes KO2, located near an elementary school, where the illuminance requirement by the standard should be 20 lx. However, in this case, the only sources of lighting for the parking area are the LED luminaires mounted along the nearby street, resulting in an illuminance level that does not exceed 3 lx at any point in the parking area.

Of all the parking areas with insufficient illumination, SW7 stands out as one of the main residential parking areas. This is a guarded parking area, but the only source of light comes from street luminaires located near the surrounding streets. As a result, the illuminance level does not exceed 3 lx. The effect of inadequate lighting is particularly evident in the equidensitometric image of this parking area (Fig. 8c).

Parking areas near shops and supermarkets also suffer from insufficient lighting. In particular, the only source of light for the parking area at KW4, near the department store, is a fluorescent light illuminating one of the rear

[3] It is possible that the luminaires illuminating this parking area are sometimes turned on during evening church services.

warehouse entrances. However, the improper lighting of the courtyard between residential blocks is a problem for the RO parking area. The illuminated areas are directly beneath the floodlights, while the parking spaces themselves remain in darkness. This is well illustrated by the equidensitometric image of this area (Fig. 8a).

In the case of interblock parking spaces illuminated by facade-mounted LED luminaires (KW..., KE..., SE..., SW...) as well as the roadside parking area illuminated by street luminaires (e.g. S1, S2, S3, S4), significant variations between the minimum and maximum values of illuminance measured in a given parking area are noticeable. This is due to the uneven spacing of street luminaires or the insufficient placement of facade-mounted luminaires (typically three per block with a length of several tens of metres). This can also be observed in the sample graphs (Fig. 7).

In some cases (e.g. S5, D4), the significant variation in illuminance within the parking areas is caused by trees, which significantly reduce the lighting in certain areas.

8. Conclusions

The lighting of parking areas in the Podwawelskie housing estate undoubtedly requires adjustments. To reduce upward light emissions and consequently decrease the brightness of the artificial sky glow above the city, it is necessary to replace the pavement of the illuminated areas with lower light reflectance material. This will also reduce the effect of illuminating apartment windows through light reflected from the pavement. Additionally, the tilt angle of facade lighting luminaires should be checked to ensure that they primarily emit light below the horizontal plane. If possible, replacing LED luminaires with MH luminaires would be desirable (Fryc & Tabaka, 2017). In some cases, for street luminaires such as BW3, reducing the height of the poles while simultaneously reducing the power of the luminaires could be considered.

To improve the lighting of parking areas, the following actions should be taken:

- Throughout the entire housing estate, it is necessary to abandon HPS park luminaires. As demonstrated, they do not fulfil the function of illuminating pedestrian paths (Ścieżor, 2022) or parking spaces.
- Each parking area in the housing estate should be illuminated by its parking luminaires (LED or MH type), independent of the street or pedestrian lighting. This is especially important for general housing estate parking areas, such as SW7.
- It is important to monitor trees growing near the luminaires and, whenever possible, prune their crowns to ensure that the light from the luminaires illuminates the ground and does not get lost in the tree canopies.

After implementing these improvements, the parking areas in the Podwawelskie estate will remain adequately illuminated while minimising environmental impact and inconvenience to residents. This will ensure the safety of parked vehicles while creating a more pleasant and harmonious living environment for the community.

References

Bąk, J. (1981). *Technika oświetlania*. Warszawa: WNT.

Brons, J., Bullough, J., Rea, M. (2008). Outdoor site-lighting performance: A comprehensive and quantitative framework for assessing light pollution. *Light. Res. Technol.*, 40, 201–224. https://doi.org/10.1177%2F1477153508094059

Crawford D. L. (1997). Photometry: terminology and units in the lighting and astronomical sciences. *The Observatory*, 117, 14–18.

Du, J., Zhang, X., King, D. (2018). An Investigation into the Risk of Night Light Pollution in a Glazed Office Building: The Effect of Shading Solutions. *Building and Environment*, 145. https://doi.org/10.1016/j.buildenv.2018.09.029

Elvidge, C.D., Baugh, K.E., Zhizhin, M., Hsu, F.-C. (2013). Why VIIRS data are superior to DMSP for mapping nighttime lights. *Proc. Asia-Pac. Adv. Netw.*, 35, 62. https://doi.org/10.7125/APAN.35.7

Fila, K., Furman, M., Gintowt, J. (2014). Illumination of architecture. The problem of light pollution. *Technical Transactions*, 5-B, 85–90. https://doi.org/10.4467/2353737XCT.14.341.3652

Fryc, I., Tabaka, P.(2017), Zanieczyszczenia nocnego nieboskłonu światłem emitowanym przez oprawy oświetlenia zewnętrznego. *Przegląd Elektrotechniczny*, 93(6), 46–49. https://doi.org/10.15199/48.2017.06.12

Guanglei, W., Ngarambe, J., Kim, G.A. (2019). Comparative Study on Current Outdoor Lighting Policies in China and Korea: A Step toward a Sustainable Nighttime Environment. *Sustainability*, 11, 3989. https://doi.org/10.3390/su11143989

Helbich, M., Browning, M.H.E.M., Huss, A. (2020). Outdoor light at night, air pollution and depressive symptoms: A cross-sectional study in the Netherlands. *Sci. Total Environ.*, 744, 140914. https://doi.org/10.1016/j.scitotenv.2020.140914

Kobav, M.B., Eržen, M., Bizjak, G. (2021). Sustainable Exterior Lighting for Cultural Heritage Buildings and Monuments. *Sustainability*, 13, 10159. https://doi.org/10.3390/su131810159

Parkins, K. L., Elbin, S. B., Barnes, E. (2015). Light, glass, and bird-building collisions in an urban park. *Northeast. Nat.*, 22, 84–94. https://doi.org/10.1656/045.022.0113

PN-EN 12464-2 (2023) PN-EN 12464-2:2014-05, Polski Komitet Normalizacyjny. https://sklep.pkn.pl/pn-en-12464-2-2014-05e.html (access: 31.05.2023).

Pothukuchi, K. (2021). City Light or Star Bright: A Review of Urban Light Pollution, Impacts, and Planning Implications. *J. Plan. Lit.*, 088541222098642. https://doi.org/10.1177%2F0885412220986421

SMD-LED (2023). Oświetlenie parkingu – normy i wymagania, SMD-LED. https://www.smd-led.pl/blog/oswietlenie-parkingu-normy-i-wymagania/ (access: 31.05.2023)

Ściężor, T. (2012). Effect of the low and high clouds on the local and distant light pollution. *Technical Transactions*, 23, 253-260. https://doi.org/10.4467/2353737XCT.14.065.1842

Ściężor, T. (2018) *Naturalne i antropogeniczne czynniki łuny świetlnej nocnego nieba*. Kraków: Wydawnictwo Politechniki Krakowskiej.

Ściężor, T. (2019). Instalacje oświetleniowe a problem zanieczyszczenia świetlnego. *Instal*, 5(406), 28–33.

Ściężor, T., Czaplicka, A. (2022), Instalacja oświetleniowa kompleksu biurowego jako źródło zanieczyszczenia świetlnego. *Instal*, 6, 35–42. https://doi.org/10.36119/15.2022.6.5

Ściężor, T., Czaplicka, A. (2023), Instalacja oświetleniowa placu parkingowego jako źródło zanieczyszczenia świetlnego. *Instal* [in print].

Tähkämö, L., Partonen, T., Pesonen, A.-K. (2019). Systematic review of light exposure impact on human circadian rhythm, *Chronobiol. Int.*, 36(2), 151–170. https://doi.org/10.1080/07420528.2018.1527773

Walker, M.F. (1977). The Effects of Urban Lighting on the Brightness of the Night Sky. *Publications of the Astronomical Society of the Pacific*, 89, 405–409.

Wiśniewski, A. (2013). *Sources of light*. Warszawa: COSIW.

Wolfe, R.E., Lin, G., Nishihama, M., Tewari, K.P., Tilton, J.C., Isaacman, A.R. (2013). Suomi NPP VIIRS prelaunch and on-orbit geometric calibration and characterization. *J. Geophys. Res. Atmos.*, 118, 11508–11521. https://doi.org/10.1002/jgrd.50873

Zielińska-Dąbkowska, K.M., Xavia, K., Bobkowska, K. (2020). Assessment of Citizens' Actions against Light Pollution with Guidelines for Future Initiatives. *Sustainability*, 12, 4997. https://doi.org/10.3390/su12124997