Practical Evaluation of Light Pollution Problem in Urban Lighting with “Decision Tree” Method

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Abstract: *Light pollution, which started in the late 20th century and spread more rapidly than predicted, is an environmental problem. Due to the increasing city life, urban lighting become essential to continue social daytime activities at night. In addition to visual lighting, with the evolution of "the image of the city" concept, the lightening process of the components that constitute the perception of the city image has begun. Unplanned and uncontrolled urban lighting applications have increased. Since light pollution is an interdisciplinary field in terms of its cause types and outcome effects, varied researches have been conducted on light pollution control techniques, and a number of standards or reports have been published by public authorities and international organizations. Today, light pollution control recommendations have increased and become more complex. A simplification of the subject is needed in order to evaluate the light pollution problem in urban lighting projects practically. The decision tree is a solution model that simplifies a problem involving a large number of factors, through the sequential evaluation of multiple decisions and using graphical support. In this study; forms of light pollution are explained, lighting principles and limit values that will reduce light pollution are reviewed in accordance with the standards and reports published by international organizations, and a practical guide that could be utilized in urban lighting projects is formed by using the "decision tree" developed in the light of this data. This study aims to contribute to increased architectural participation in solving the light pollution problem.*

Keywords: *Light Pollution, Urban Lighting, Decision Tree*

Işik Kirliliği Sorununun Kent Aydinlatma Projelerinde “Karar Ağaci” Yöntemi ile Pratik Değerlendirilmesi

Özet: *Işık kirliliği; 20 yy’ın sonlarında başlayan ve öngörülenden hızlı bir şekilde ilerleyen çevresel bir sorundur. Artan kent hayatı sebebiyle kentlerin gündüz işlevlerinin gece de devam etmesi toplumsal bir ihtiyaç haline gelmiştir. İşlevsel aydınlatmanın yanı sıra; “kent imajı” kavramının gelişmesi ile kent algısını oluşturan ögelerin aydınlatılması süreci başlamıştır. Kent aydınlatma uygulamaları plansız ve kontrolsüz bir şekilde artmıştır. Bu sebeple; nedenleri ve sonuçları itibariyle interdisipliner bir alan olan ışık kirliliği önlemlerine yönelik çok yönlü araştırmalar yapılmış, kamu otoriteleri ve uluslararası organizasyonlar tarafindan çok sayıda standart ve rapor yayınlanmıştır. Günümüzde, ışık kirliliği önlemlerine yönelik veriler artmış ve karmaşıklaşmıştır. Işık kirliliği sorununun kent aydınlatma projelerinde pratik bir şekilde değerlendirilebilmesi için konunun sadeleştirilmesine ihtiyaç vardır. Karar ağacı; çok sayıda değişkene bağlı bir problemi grafik desteği ile, birden fazla kararın ardışık değerlendirilmesi sonucu sadeleştirerek sonuca ulaştıran çözüm modelidir. Bu çalışmada; ışık kirliliği biçimleri açıklanmış, uluslararası kuruluşların yayınladığı standartlar ve raporlar doğrultusunda ışık kirliliğini azaltacak aydınlatma ilkeleri ve sınır değerler irdelenmiş ve bu bilgiler ışığında geliştirilen “karar ağacı” aracılığıyla kent aydınlatma projelerinde kullanılabilecek pratik bir rehber oluşturulmuştur. Yapılan çalışma ile; ışık kirliliği sorununun çözümüne yönelik mesleki katılımın artmasına katkı sunulması hedeflenmiştir.*

Anahtar Kelimeler: *Işık Kirliliği, Kent Aydınlatma, Karar Ağacı*

1. INTRODUCTION

Environmental conditions are described by individuals through their sensory systems. Perception of these conditions is formed by analyzing visual, auditory, and thermal signals based on personal subjective criteria. Daylight, which provides visual perception, disappears with the onset of night, unlike other environmental conditions. Since moonlight does not provide sufficient visual conditions, artificial light sources have been used throughout history to brighten the night. The first light source used for this purpose was fire. Later on, oil lamps, torches, candles and gas lamps were used. Starting at the end of the 20th century, electric power became the primary means of lighting, followed by the invention of the incandescent lamp. Lighting technology has continued to develop rapidly to the current day [1].

The advances in lighting technology have expanded the capacity to illuminate cities, thus making them safer and more secure, while also enabling the continuation of daytime activities such as shopping, education, entertainment, and transportation during the evening hours. During the second half of the 20th century, there was a growing recognition of the importance of the urban image. The purpose of the lighting is not only to serve functional needs, but also to highlight prominent features, such as iconic buildings, streets, trees, or sculptures, that constitute the image of the city, in order to visualize the identification of the city that is perceived both during the day and at night [2]. Over time, there has been a significant increase in the number of objects and areas that are illuminated, almost resulting in a contest for lighting between cities. The uncontrolled and unconscious utilization of lighting techniques, compounded by the growing urban population and the development of lighting technology, has brought the problem to a faster pace than predicted, and the darkness of the night has been substituted by the glowing nights [3]. In addition to skyglow, light trespass, energy waste, and glare caused by inappropriate lighting fixture selection or uncontrolled night lighting designs that are not appropriate in terms of quantity and quality are also considered light pollution. In addition to sky glare; light trespass, energy-waste, and glare, which are caused by improper luminaire selection or unregulated over-lighting designs with high levels and poor quality, are also defined as light pollution [4]. Many studies reveal that light pollution has several negative impacts on astronomical observations, human health, and the ecological system [5-8]. This demonstrates that urban lighting should be organized in a planned manner, limit values should be determined, and appropriate lighting techniques should be utilized [9-11].

Light pollution is a multidisciplinary problem in terms of its causes and consequences. Illuminated streets and avenues to ensure safety and security, leaking lights from factories and workplaces due to night shifts, lightening of parks, squares and walkways to perpetuate day-time urban activities, facade lighting that continues urban memory, billboards, vehicles, greenhouses, improperly installed direct lights, reflected lights and passing lights all cumulatively cause light pollution [12]. From an outcome perspective, there is a large amount of research on the effects of light pollution on astronomical observations, human health such as cancer, obesity, sleep disorders, or environmental issues related to biodiversity, food security, energy consumption, or economic and environmental sustainability [5, 13-19]. The illumination of building facades and recreational areas is critical for architectural studies. However, today, the problem of light pollution, which is interdisciplinary in terms of its causes and consequences, has turned into a comprehensive problem that cannot be analysed in architectural design phases. In order to increase awareness and architectural participation in this problem, there is a demand for simplified methods where lighting luminaries, techniques and regulations can be evaluated in a practical manner from the perspective of light pollution [20].

This study, presents the explanations of sky-glow, glare, light trespass, and energy-wastage that are terms revealed by light pollution, has a review of the lighting principles to reduce light pollution. In view of these notions, a practical guide is established for urban lighting projects by means of the "decision tree" developed in this study.

2. FORMS OF LIGHT POLLUTION

Light pollution is defined as artificial lighting which alters the level of the natural light sources and, may result in sky glow glare, light trespass and excessive illumination [21]. Unplanned or inadequate light use, such as over-illumination of a building facade or urban area with improper location and orientation, causes this problem.

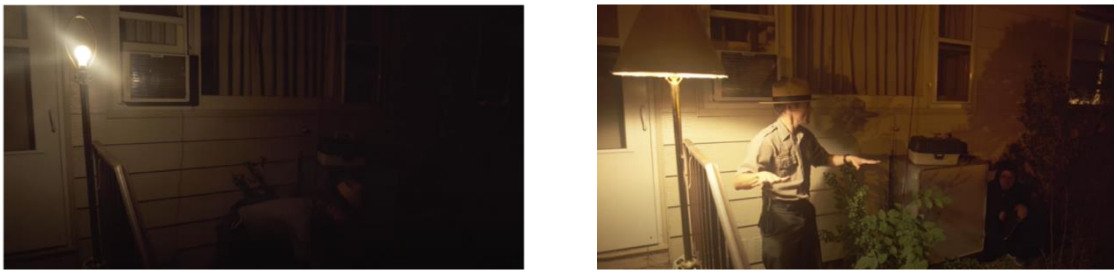
2.1. Sky-Glow

The first term used to define light pollution was "sky glow" which caused discomfort glare occurred by the excessive use of light through astronomical observations, and this definition was synonymised with light pollution till the early 21st century [22-24]. The light emitted upwards from lighting fixtures and reflected from the ground into the sky is transported to the sky through dust and air molecules in the atmosphere. From a distance, this phenomenon is visible like a luminous dome and described as "sky-glow" (Figure 1).

Figure 1. "Sky glow" caused by the unshielded upward lights to the sky [25]

2.2. Glare

Glare is described as the perception of visual discomfort caused by high luminance contrasts which the system of vision can not accommodate [26]. Glare is considered in two types, "direct glare" caused by direct light emitted from the light sources and " reflected glare" caused by the light reaching the eye by specular reflection through glossy surfaces [14]. In both cases, due to the eye's accommodation to high levels, the immediate peripheral surfaces are perceived as dark and visual comfort is deteriorated (Figure 2, Figure 3).



(a) *(c)*

Figure 2. Visual discomfort caused by "direct glare" (a) The immediate peripheral surfaces are perceived as dark, the vicinity environment can be seen clearly after redirecting the light to the target area (c) [27]

Figure 3. Inability to identify horizontal and vertical surfaces of stairs due to glare (Photo copyright: Christopher Kyba)[28]

2.3. Light Trespass

Light trespass is defined as the disruptive effects that occur as a result of undirected lighting in non-targeted neighbourhood areas [29]. Light trespass is observed commonly in dwellings which are close to inappropriate shielded street lightings and in closely located neighbouring buildings [30] (Figure 4). Light trespass is one of the most important notions in raising social awareness against light pollution since the number of people affected in daily life, especially residential users, is high [31].

(a) (b)

Figure 4. Light trespass caused by door lighting (a) [32] and caused by unshielded street lighting (b) [33]

2.4. Excessive Lighting

Excessive lighting refers to lighting higher than required levels, which are recommended/limited by standards and regulations for optimal visual conditions, or prolonged lighting due to not using control systems with daylight/motion sensors [34].

3. LIGHTING PRINCIPLES TO REDUCE LIGHT POLLUTION

The social activities that brought with urban life, the use of roads at night, entertainment culture, the demand to make cities safe and secure, the concept of "city branding" that began after the 18th century, and the awareness of generating tourism revenue have turned the illumination of cities into a social necessity [35]. Therefore, the way to prevent light pollution is not to darken cities by not illuminating them, instead, it should be to design dark-sky-friendly cities. Since light pollution is the excessive use of light for an unnecessary area or building with design flaws that cause energy waste, the designer should make a 3-step questioning before starting the lighting design in order to avoid causing light pollution.

- Is this lighting design needed?
- Are the appropriate lighting fixtures selected?
- What are the illumination thresholds?

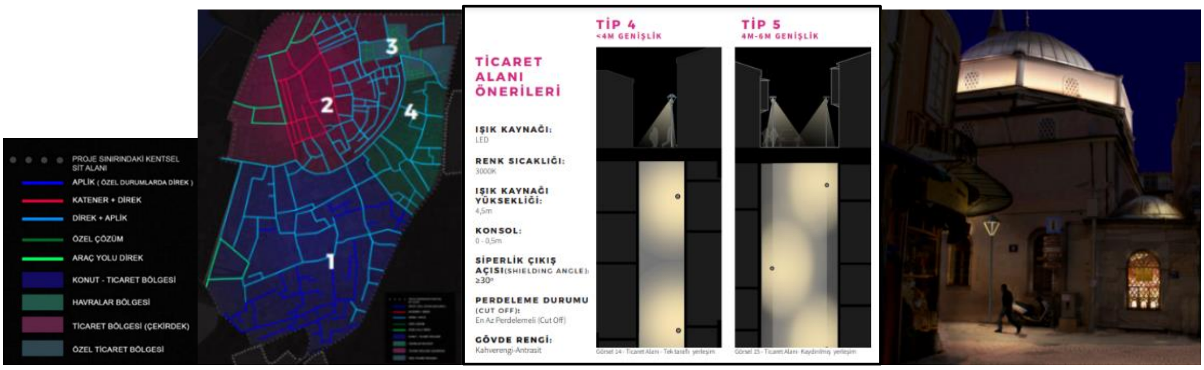
To achieve dark-sky friendly urban lighting; zoning regions or designing a lighting master plan, proper lighting fixture selection, and not exceeding the limit values is essential [36].

3.1. Lighting Master Plan

Similarly with several forms of urban design, a comprehensive approach is crucial for urban lighting. Haphazardly prepared, individual lighting designs that are incoherent and without an integrative design approach do not contribute to making the city an attractive or safe place, since they are not perceived as a part of the whole. Therefore, decisions on urban lighting should be made according to the "lighting master plan", which is prepared by considering zoning, appropriate lighting techniques and limit values based on economic, social and environmental analyses extending from the macro to the micro scale. The lighting master plan consists of analysis, design and simulation phases. In the analysis phase, existing lighting conditions are studied, regionalization is carried out considering the elements that constitute the perception of urban identity, and individual buildings with urban character are identified. The following elements play an important role in the perception of urban identity, which allows the continuation of the daytime urban experience at night [2];

- Zones determined by functional characteristics such as commercial, residential, industrial or historical background.
- Boundary lines that constitute zones such as wide highways, rivers, forests
- Transportation arteries with varied intensity and time span of occupancy such as roads, streets, squares
- Historical artifacts, commercial or public buildings that contribute to urban memory
- Landmarks such as statues, bridges, mausoleums

In the design phase, a lighting hierarchy is defined for zones, lighting scenarios are created for individual buildings, technical specifications of the luminaries that do not cause light pollution are determined and installation proposals are prepared. In the simulation phase, calculations and visualizations of the design proposals are complemented through software (Figure 5).



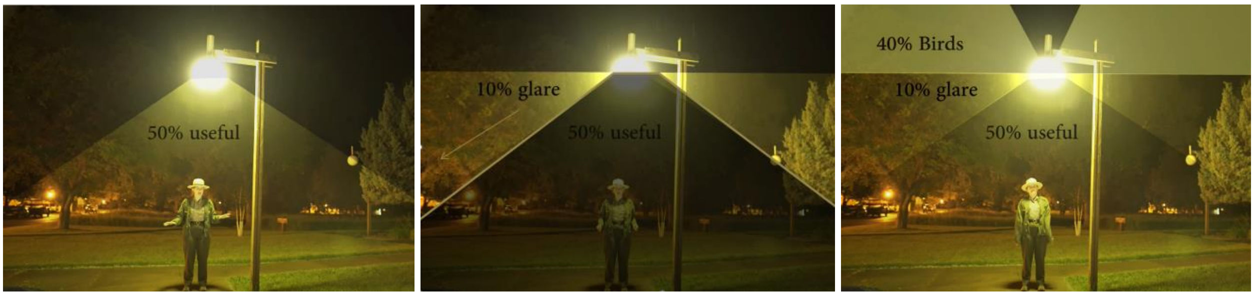
(a) (b) (c)

Figure 5. Phases of lighting master plan (a) Determining lighting hierarchy for zones (b) Technical properties and installation recommendations for luminaries (c) Simulation of lighting scenarios for individual buildings [37]

3.2. Selecting Appropriate Lighting Fixtures

In many cases, the light emitted from the lamp is not oriented to the target area and cannot provide good visual conditions or avoid energy wastage. Therefore, lighting fixtures (luminaries) that redirect the light are used. The technical requirements differ depending on whether the luminaries are used in indoor or outdoor environments. In order to select the appropriate fixture that will not cause light pollution from a large number of options available in the lighting industry, technical features such as spatial light distribution, cut-off angle, light colour, luminaire efficiency, protection class, and scotopic/photopic ratio should be evaluated.

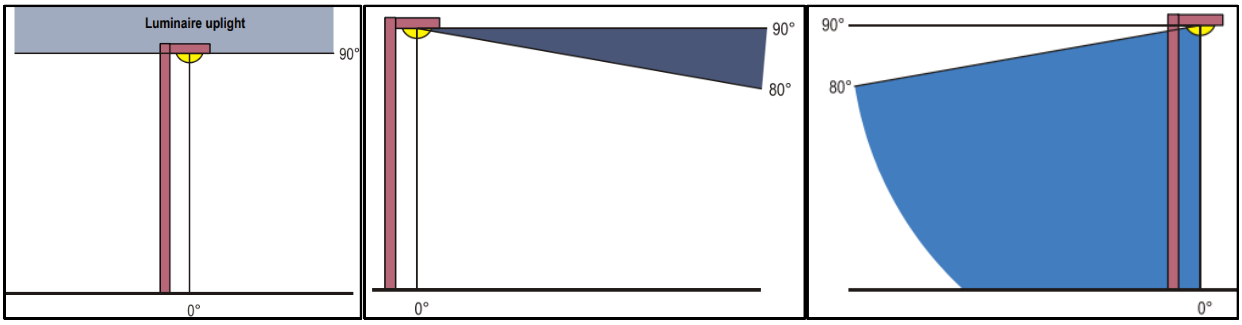
Spatial light distribution refers to the distribution of light from a light source into an equidistant sphere and is crucial for avoiding lighting of untargeted areas as well as achieving uniformity of illumination. The aim of illumination is to make an object or its surroundings visible by applying light [38]. Therefore, the target is the area to be illuminated. Light scattered outside the target area constitutes light pollution, by causing sky glow, energy-waste, light trespass and glare. The spatial light distribution of a luminaire used for outdoor lighting is evaluated in Figure 6. The target area to be illuminated is the walkway where the pedestrian is standing and its surroundings. This means that only 50% of the luminous flux emitted from the lamp is directed to the target area. 10% of the light is directed like a torch shining from a high altitude, causing direct glare for pedestrians or vehicles outside the target area and light trespass for nearby buildings. The remaining 40% of the luminous flux is directed upward, illuminating the sky and causing sky glow. Therefore, 50% of the light emitted from the fixture is scattered in the off-target area and causing energy waste. This indicates that all forms of light pollution can occur as a result of fixture selection with inappropriate spatial light distribution.



(a) (b) (c)

Figure 6. Evaluating spatial light distribution (a) Useful luminous flux for target area (b) Luminous flux cause direct glare like a high altitude torch (c) Upward light that occur sky glow [27]

Spatial light distribution should be specific for each architectural project and designed in line with the lighting intent. The target area for illumination has to be defined clearly. The luminous flux should not be directed upwards or backwards to the area that is not intended to be illuminated, or to the area at an angle of 80° - 90°, which will cause glare (Figure 7). The luminous flux should not be redirected to the area that is not intended to be illuminated upwards, backwards or to area at the angle of 80°- 90° which causing glare. While upward lighting is not preferred for roadways because it is a source of light pollution, it is preferred for architectural facades. In this point, luminaries with asymmetric intensity distribution should be used for façade lighting, which illuminates the target surface but does not emit light to the sky. Figure 8 demonstrates various outdoor lighting scenarios featuring luminaires possessing significantly different light intensity diagrams. This phenomenon demonstrates the importance of evaluating the light intensity diagram on a per-project approach.



(a) (b) (c)

Figure 7. Forms of lighting not to target area (a) Causes sky-glow (b) Causes glare (c) Causes light trespass [39]

(a) (b) (c)

Figure 8. Luminaries and light intensity diagrams for diverse activities. (a) Two-sided walkway lighting [40] (b) Arched building lighting [41] (c) Single-sided walkway lighting [42]

Upward light ratio (R_{UL}) varies between 0-25% in EN 12464-2 European Committee for Standardization [43] "Light and lighting - Lighting of work places - Part 2: Outdoor work places" standard and the limit values increase from rural areas to the town centers or commercial areas (
Table 1).

Table 1. Limits for upward lighting according to European Committee for Standardization [43]

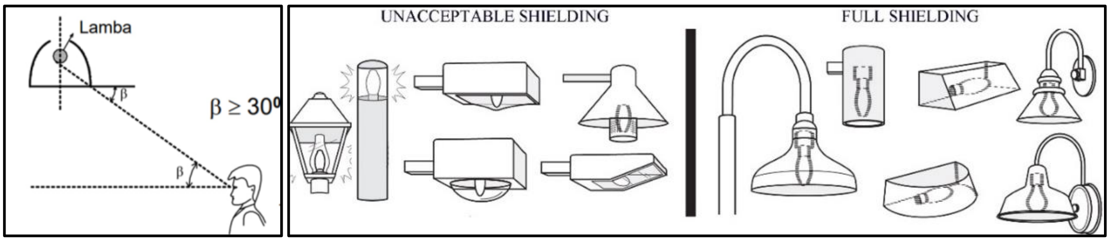
	Dark areas, such as national parks or protected sites	**Low district brightness areas, such as industrial or residential rural areas**	**Medium district brightness areas, such as industrial or residential suburbs**	**High district brightness areas, such as town centers and commercial areas**
$\mathbf{R_{UL}}$	0%	5%	15%	25%

In the classification made by the Illuminating Engineering Society of North America (IESNA), the ratio of upward light, which causes sky glow, and the ratio of light emitted in the area between 80°-90°, which causes glare, are taken into account [44, 45]. Luminaries are categorized under 4 groups: full cutoff, cutoff, semi-cutoff, non-cutoff (Table *2*). Today, due to the increasing awareness of light pollution, the options for fully cutoff fixtures have increased and their accessibility has become easier. Considering the increasing rate of light pollution not only in rural areas but also in city centers and the availability of cutoff devices, it is concluded that following the IESNA recommendations instead of the EN 12464 standard is more convenient in terms of sky glow prevention.

Table 2. Cutoff classification of IESNA (Adapted from IESNA-RP-8-00 [44] and IESNA-RP-33-99 [45])

	Full cutoff	**Cutoff**	**Semi-cutoff**	**Non-cutoff**
The ratio of upward lighting	0%	2,5%	5%	More than 5%
The ratio of light emitted into area between 80°-90°	10%	10%	20%	More than 20%

Uniformity of illuminance (U_0) is determined by the ratio of the lowest illuminance level to the average illuminance level. This ratio should be in the range of 0,25-0,40 according to EN12464-2 [43] and 0,17-0,33 according to IESNA-RP-8-00 [44] for pedestrian paths.
The shielding angle is the angle between the horizontal plane and the boundary line that the light source in the fixture can be observed. It is usually provided via an opaque or translucent material in order to block the light emitted from the lamp and reaching directly to the eye. While the spatial light distribution of a fixture is appropriate, the perception of the light source in the viewing field may cause direct glare and light pollution. For equipment using high luminance light sources (>500kcd/m²) and the area from which the luminous flux is emitted is left open or covered with materials generating direct transmission, the shielding angle should not be less than 30° to avoid direct glare [14]. However, it would be more prudent to prefer solutions where full shielding is provided (Figure 9).



(a) (b)

Figure 9. a) Determining shielding angle (b) Acceptable and full shielding examples [46]

Light color is associated with the spectrum (wavelength) of light and is quantified by there metrics, correlated color temperature, color appearance and color rendering [47]. Correlated color temperature refers to the temperature of the blackbody (Planck radiator) whose perceived colour is the same as the light source under specific measurement conditions [48]. It is expressed in Kelvin, a unit used to measure temperature. As the color temperature of light emitted by a light source increase, the blue light component intensifies and the potential for harm to human health and the ecological system increases.

Color appearance is the intuitive expression of the light perceived as, such as warm, intermediate, or cool. Light with a color temperature below 3300 K is considered "warm", between 3300-5300 as "intermediate", 5300 K and above as "cool" colored light [43] (Figure 10). The choice of color temperature is a design issue. However, considering the effects of blue light on human health, the benefits of choosing a warm colored light are appreciated [49]. Warm colored lights are reminiscent of the color impression of light sources such as fire, candles, gas lamps, incandescent lamps used in night lighting. Therefore, it is recommended to use warm colored light sources in harmony with human history and that do not cause as much damage to public health as blue light [50].

Figure 10. Color temperature and color appearance of light [51]

Color rendering indicates the light source's ability to display objects in their original color. It is measured with the Ra index, with values from 1 to 100, where 100 represents the best color rendering. As the color rendering index (Ra) decreases, objects appear more faded and grayed out, losing their original color. The color rendering index (Ra) values of lighting fixtures in the range of 20-40 is classified as "poor", those in the range of 40-60 as " moderate", those in the range of 60-80 as "good", those in the range of 80-90 as "very good" and those in the range of 90-100 as "excellent". In the literature, it is recommended that lighting fixtures with poor or moderate color rendering class may be used for road lighting [43, 52]. However, current research indicates that the color rendering class is also important in street lighting. ARUP [37] specified that sodium vapor lamps with low color rendering class cause changes in the color of vehicles or clothing. In the report published by International Commission on Illumination [53], it is noted that monochromatic light sources with low color rendering should be avoided, especially in pedestrian path lighting. TS EN 12301-2 [54] the Road lighting - Part 2: Performance requirements standard, stated that high color rendering contributes to face recognition. The EN12464-2 [43] standard states that high color rendering contributes to good visual environment. In addition, the color change in architectural buildings, which are illuminated in order to perpetuate urban character, is incompatible with daytime memory and does not contribute to the purpose of illumination. It is recommended that the Color Rendering Index (Ra) should be greater than 60 in order to perceive the original colors of objects, distinguish color differences, and ensure safety in public spaces [52]. Also, fixtures with a "poor" or "moderate" color rendering class should not be used in areas where color vision is important [55]. In the context of these considerations, choosing fixtures with a color rendering index higher than 60 is advisable to provide good visual conditions, create urban lighting, which is compatible with daytime memory, and ensure safety in public spaces.

Efficient energy use can be defined as reducing energy consumption without compromising good visual conditions. Energy efficiency in urban lighting is achieved by reducing the energy consumed for unit area and turning off or dimming the light when it is not needed. Therefore, the luminous efficacy of the lamp and the efficiency of the luminaire should be high, also control systems with daylight and/or motion sensors should be used. While the luminous efficacy of a 100W incandescent lamp is 13.8 lm/W, the luminous efficacy of a halogen lamp is 15-16 lm/W, and the luminous efficacy of a fluorescent lamp is in the range of 65-80 lm/W depending on the phosphor type. Today, thanks to the technological development in the lighting industry, the luminous efficacy of LEDs has increased up to 130 and is still growing. When choosing a lamp, high luminous efficacy should be taken into account. Luminaire efficiency is the ratio of the luminous flux emitted from the fixture to the luminous flux emitted from the lamp [38]. Energy consumption decreases as the luminaire efficiency value approaches 100%. Therefore, when comparing fixture options, the one with the closest efficiency to 100% should be preferred. In order to avoid redundant energy consumption, exterior lighting should be dimmed by 50% after 02:00 and should be turned off after daylight levels reach a required level [56]. This requires the use of automation systems with "dimming" capability and timed settings. Also, automation systems that can be controlled from the central system through wireless networks may be considered for outdoor lighting [57].

The protection classes of the fixture should be tailored to the physical environment such as temperature, humidity, and dust. These classes are determined in accordance with the two-numbered IP (Ingress Protection) system in TS 3033 EN 60529 [58] standard and the IK system in TS EN 62262 [59] standard. The IP system consists of two numbers. The first number indicates protection against solid objects such as rock, soil, dirt or dust and the second number indicates the protection class against liquids. The IK system refers to the protection class against mechanical impacts measured in "joules". At least IP54 class, partially dust-proof and protected against splashing water from all directions, must be provided for exterior lighting equipment [60]. In the 2013 Lighting Regulation, it is stated that the fixtures should provide long-term protection against dust and contamination [56]. The Lighting Handbook prepared by SLL notes that as the IP rating of equipment decreases, the maintenance factor value decreases, and that at least IP55 should be provided for exterior conditions [52]. IP55 and IP54 classes are not dustproof, but partially protected against dust. Considering the conditions of the outdoor environment in urban areas, it is considered preferable to use IP65 or IP66 protection classes, which are available today in many companies of the lighting industry, having full protection against dust and water jets, and IK08 class with 5 joule impact resistance against mechanical impacts, in order to avoid reducing the maintenance factor value [58, 59].

The scopic/photopic (S/P) ratio is an index that quantifies the difference in the perception of illuminance level under daytime-seeing (photopic) and night-seeing (scopic) conditions, depending on the adaptive mechanism of the eye optic. The cones and rods in the human eye are active at different illuminance levels. The cones are active in daytime seeing (photopic) at illuminance levels of 10 cd/m² and above, whereas the rods are active in nighttime seeing (scopic) at illuminance levels of 0.001 cd/m² and below [61]. Cases between these two conditions are defined as evening seeing (mesopic) [62]. In photopic seeing, the highest sensitivity in the relative responsivity curve of the eye is at 555 nm. Under night vision conditions, the relative spectral responsivity moves towards shorter wavelengths and the sensitivity differs from day seeing conditions [63]. This causes changes in the luminous flux values and precepted luminance levels. The light containing blue light in its spectrum is perceived with higher luminance, than the others even if the color appearance is the same. However, lamp lumen output is a function of photopic conditions. The report published by the CIE draws attention to this situation and states that mesopic visual conditions should be taken into account in street lighting to ensure good visual conditions, reduce light emissions and save energy [53]. Since S/P ratio measuring fixtures are not yet widely available, measurements related to exterior lighting designs are based on photopic evaluations without considering the physical behaviour of the human eye [64]. Today, LED technology makes it possible to provide luminaires that have the same color rendering and color appearance with different S/P ratios thus it is possible to save energy by using luminaires whose S/P ratios are high [37]. The table in BS EN 5489-1 [65] , which recommends illuminance levels for road lighting with different densities, presents gradually decreasing "average illuminance level" and "minimum illuminance level" values for light sources with S/P ratios, unknown, 1,2 and 2,0. [65]. As the S/P ratio is a new approach, studies to determine limit values and measurement methods are ongoing. Manufacturers do not yet share the S/P ratio of their products as widely as other technical specifications. Even though this situation makes evaluation of the S/P ratio difficult in luminaire selection, this innovative approach should not be ignored. In case the S/P ratio is known, the values given in BS EN 5489-1 [65] standard should be taken as reference and the developments on the subject should be followed.

3.3. Limit Values for Illuminating

Since urban lighting has become a public need, it is not possible to switch the exterior lighting off. Nevertheless, considering the effects of light pollution, it is essential to limit unplanned and uncontrolled lighting. In this context, international organizations and public authorities set limit values for the illumination of pedestrian paths and building facades, which concern the discipline of architecture. In standards and regulations, the CIE's environmental zoning is considered, thus taking a stance towards the protection of dark areas with high sensitivity [52]. In EN 12464-2 [43] standard, lighting limits are determined according to the environmental zone classification and the before/after curfew time. The curfew starting time is set as 02:00 in the Lighting Regulation [56]. Whereas the regulation states that the blackout should be 50%, higher values are recommended in the standard (Table 3).

Table 3. Recommended limits for exterior lighting in EN 12464-2 [43] standard

Zone	**Definition**	**Maximum vertical Illuminance on properties (lx)**		**Luminance on building façade (cd/m²)**
		Pre-curfew	**Post-curfew**	
E1	Dark areas, such as national parks or protected sites	2	0	0
E2	Low district brightness areas, such as industrial or residential rural areas	5	1	5
E3	Medium district brightness areas, such as industrial or residential suburbs	10	2	10
E4	High district brightness areas, such as town centres and commercial areas	25	5	25

For pedestrian paths, the visibility of the walkway, the perception of approaching pedestrians and the discrimination of obstacles are important. Hence, in addition to the horizontal illuminance level achieved on the floor, the vertical illuminance at eye level and semi-cylindrical illuminance for face recognition should also be considered. [53]. TS EN 13201-2 [54] has specified illumination limits for pedestrian paths at floor level and for the plane 1,5 m above ground level (Table 4).

Table 4. Limit values for pedestrian paths [54, 66]

Zone	**Definition**	**Horizontal illuminance on road level (lx)**		**Illuminance at 1,5 m above the road level (lx)**	
		Average	**Minimum**	**Vertical**	**Semi-cylindrical**
P1	High prestige roads	15	3,0	5,0	3,0
P2	Heavy night-time use by pedestrians or pedal cyclists	10	2,0	3,0	2,0

P3	Moderate night-time use by pedal cyclists or pedestrians	7,5	1,5	2,5	1,5
P4	Minor night-time use by pedal cyclists or pedestrians solely associated with adjacent properties	5,0	1,0	1,5	1,0
P5	Minor night-time use by pedal cyclists or pedestrians solely associated with adjacent properties. Important to preserve village or architectural character of environment.	3,0	0,6	1,0	0,6
P6	Very minor night-time use by pedal cyclists or pedestrians solely associated with adjacent properties. Important to preserve village or architectural character of environment.	2,0	0,4	0,6	0,4

4. SIMPLIFYING THE LIGHT POLLUTION PROBLEM WITH DECISION TREE METHOD

Decision making is the process of determining the most appropriate option for a given purpose from a set of possible alternatives [67]. Today, people or businesses are faced with the necessity to make decisions based on more than one objective or metrics. A decision tree is a solution model that enables the sequential evaluation of multiple variables and provides decision support by simplifying them graphically [67, 68]. As mentioned above, light pollution is a multidimensional problem in its forms, causes and consequences. However, urban lighting is an indispensable social need today. Lighting techniques to prevent light pollution are based on many standards and criteria. There is a need to simplify the problem in order to prevent time losses and possible negative architectural applications.

In creating a decision tree, the root node, the internal nodes (branches) and the terminal nodes (leaves) are all crucial. If the tree becomes complex and the data sets cannot be tracked, the tree loses its functionality [68, 69]. Based on these considerations, the root node of the tree was the question " Is this design avoiding light pollution? The internal nodes are the basic questions mentioned above, "Is this lighting needed?", "Are the appropriate lighting fixtures selected?", "What are the illumination thresholds?", and the necessary terminal nodes are created for each question. "Yes" and "No" prompts on the branches of the tree direct the designer to decision support information according to the recommendations of relevant standards and reports (Figure 11).

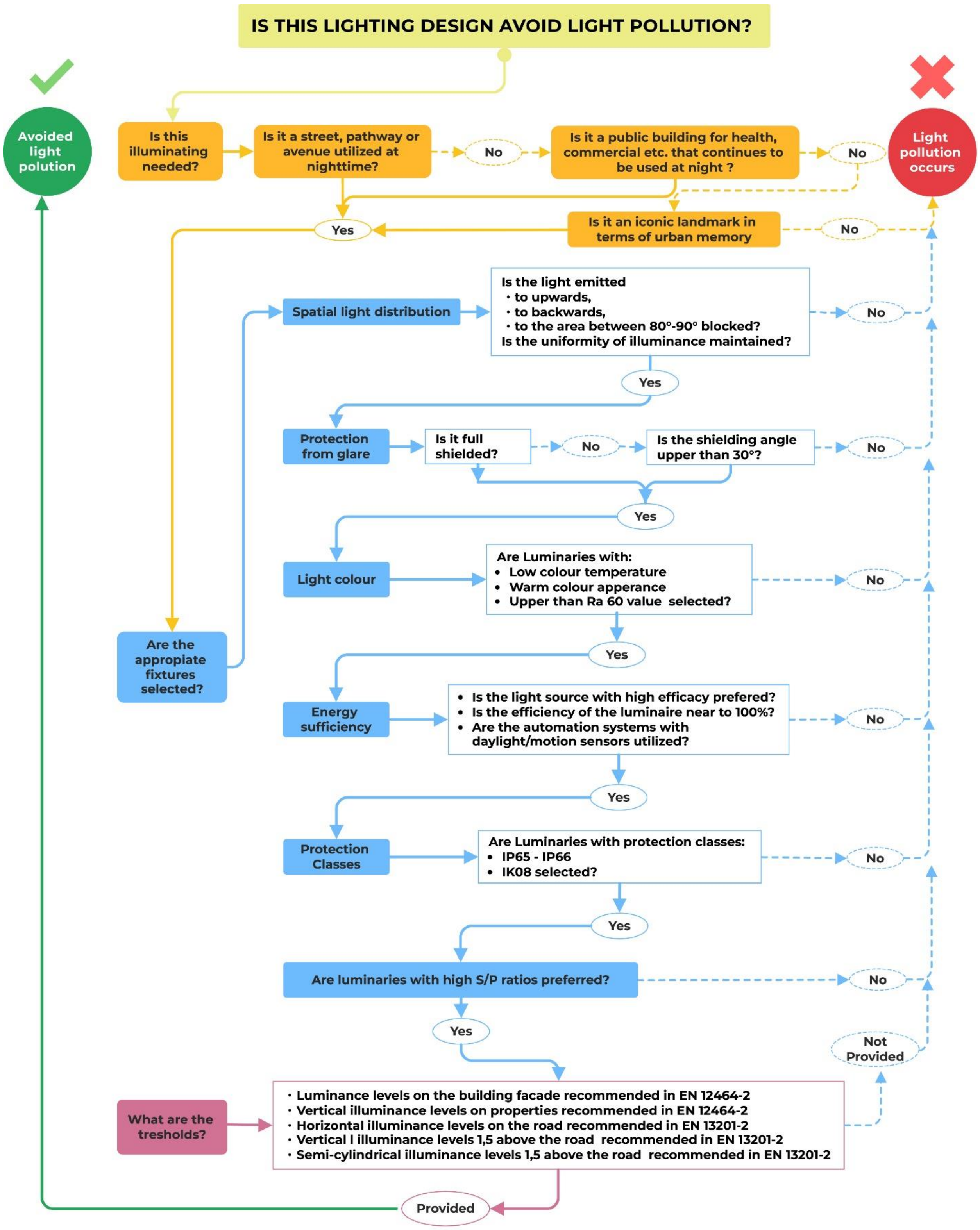


Figure 11. Decision tree for urban lighting design to avoid light pollution

5. CONCLUSION

Urban lighting means illuminating the city for users to fulfill several activities in security and safety after nightfall and to make the city more appealing. As daylight disappears, the functional and architectural illumination of cities becomes more prominent. However, lighting designs that is not in accordance with the technique and/or has a prolonged illumination period cause some drawbacks. Light pollution and increased energy consumption, which affect bioecology are the most important of these concerns.
In order to minimize light pollution, in the form of sky glow, glare, light trespass and excessive illumination, the limit values of the standards and recommendations prepared by the organizations should be followed in functional and architectural urban lighting instead of arbitrary individual designs. Fixture selection should be project-specific and compatible with architectural design and function. In addition to aesthetic requirements, technical features should also be considered. In addition, it is crucial to prepare master plans tailored to each city or to different zones within the city. It is vital to consider technical and aesthetic merits in establishing a lighting master plan, to approach the problem from a comprehensive perspective, and to organize public audits of the applications.

Lighting techniques and limits for the prevention of light pollution, which is a multidisciplinary problem with its forms, causes and consequences, have been linked to many standards and regulations. This study presents a decision tree model by systematizing and simplifying the steps to be followed in order to prevent light pollution in urban lighting design. The model decision tree is intended to establish a simplified method for taking proactive measures against light pollution and energy consumption at the beginning of the design process, and also to develop a preliminary study that can be used in the preparation of lighting master plans.

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