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Global Approaches to Reduce Light Pollution from Media Architecture and Non-Static, Self-Luminous LED Displays for Mixed-Use Urban Developments

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Abstract: Urban environments have become significantly brighter and more illuminated, and cities now consider media architecture and non-static, self-luminous LED displays an essential element of their strategy to attract residents, visitors, and tourists in the hours after dark. Unfortunately, most often, they are not designed with care, consideration, and awareness, nor do they support the visual wellbeing and circadian rhythms of humans. They also increase light pollution which has an adverse effect on the environment. The aim of this study was to estimate the scale of the negative impact of 28 non-static, self-luminous LED shop window displays within a real-life city context along the main shopping street Banhofstrasse in Zurich, Switzerland. An experimental field measurement survey investigation was performed to identify visual luminance with commonly available tools such as a luminance meter and a digital reflex camera for luminance photography. Moreover, the most important global approaches to reduce light pollution were evaluated in the form of existing guidelines, technical standards, and laws, all of which should be considered when specifying illuminated digital advertisements. A literature review and survey results both confirmed the extent of the problem and highlighted, too, the need to better measure, apply, and manage this new technology. The authors' proposal for improvements involve practical recommendations for the design and implementation of future projects which can positively guide and direct this growing trend.

Keywords: light pollution; media architecture; media facades; non-static LED displays; LED screens; illuminated digital advertisement; video displays; self-luminous surfaces

1. Introduction

In recent decades, urban environments have become significantly brighter and more illuminated (Figure 1), and cities now consider lighting an essential element of their strategy to attract residents, visitors, and tourists in the hours after dark [1,2]. Additionally, urban planners have realized that dividing a city into separate districts for specific purposes, such as residential, commercial, cultural, institutional or environmental land use, no longer works from a functional perspective for city inhabitants. After business hours, one can observe that in commercial and institutional quarters, these parts of a city can become dark and unwelcoming places with an absence of people in the streets. To overcome this problem and inject more life into certain city areas, a new trend has emerged. Mixed-use development integrates retail (i.e., shops and restaurants) enterprises which are often located on the ground floor, with commercial and residential properties on the floors above. While this change increases economic prosperity and socializing in the night hours to create livable cities [3], increased light pollution can negatively impact the area and reduce the quality of life for residents [4,5].

Figure 1. Guangzhou, China: cities now consider creative lighting an essential element of their strategy to attract residents, visitors, and tourists in the hours after dark. Source: Signify's figure.

In 2009, an approved European 2020 Strategy for climate change and energy recommended the following: minimizing greenhouse gas emissions to 20% lower than 1990 levels, the use of 20% of energy coming from renewable sources, and a 20% increase in energy efficiency that involves the employment of effective technologies such as LEDs [6].

As LED lighting is considered more energy efficient, adaptable, and cheaper to operate than older light sources, it is already in use in street lighting retrofit projects [7–9], historical urban settings [10], facade illumination [11,12], landscape lighting [13], in trials for a smart city [14], and as animated LED video advertisement displays in different forms applied to buildings [15]. According to market estimates and forecasts, the future trend of global LED video display technology will grow around 35% over the next decade, reaching approximately $73 billion by 2025 [16]. Certainly, when applied and controlled properly with suitable relevance to the building's architecture and/or the urban realm in which they are introduced, media architecture and non-static, self-luminous LED displays can positively add to the nighttime image of a city by creating a visually stimulating atmosphere [17]. But adequate guidance is necessary and one should acknowledge not all cities and towns need visual clutter. Times Square, Piccadilly Circus, and Shinjuku each have their own historical relationship with bold advertisements that create a one-of-a-kind place of identity that attracts tourists, but it is worth noting that these areas do not contain residential dwellings (city accommodations should provide adequate darkness at night for the health and wellbeing of its inhabitants).

Researchers and practitioners within the field have provided some insights into the body of knowledge of these new urban elements, from technology and prototyping [18], policy and design issues [19,20], social interaction [21], displayed context [22], to design challenges [23], aesthetics [24], and more. Alas, there is still very little research on the environmental and health impacts of outdoor media architecture [25]. Therefore, while research exists to assist our understanding of this trend and its numerous applications, more studies are required to help better apply and manage the use of this recently developed lighting technology.

This is pertinent because the majority of non-static, self-luminous LED displays today are excessively bright and without any controls in place [26,27]. This diminishes the nighttime landscape here on Earth, whilst also substantially adding to the sky glow above cities. Light pollution, also known as obstructive light, prevents astronomical observations and disconnects humanity from the night sky as well [28]. In particular, LEDs emit excessive luminance and generate unwanted glare [29]. Also, their high-intensity light restricts the pupil in the human eye, thus dark adaptation is prevented, making it impossible to detect all but the brightest stars in the sky (while the sky may appear almost black, the fine detail of the night sky becomes invisible) [30,31].

When such displays are visually too bright compared to the surroundings, they also negatively impact the movement of pedestrians and drivers [32]. Additionally, light trespass may enter the interior of residential properties at night, causing distress and insomnia [33].

As there are no worldwide established standards and recommendations regarding how to correctly design, apply, and verify the impact of media architecture and colorful, non-static, self-luminous LED displays in an urban context [34], research in this field seems to be novel and significant. Furthermore, immediate action is required by the international authority on light and illumination—the International Commission on Illumination (CIE)—to provide guidelines to reduce the impact of artificial light at night (radiating from these lighting features) on all end users (humans, flora, and fauna), and to encourage respect for the nighttime urban landscape, while at the same time, supporting business and event advertising, and ensuring easy navigation and wayfinding in cities.

Ideally, there ought to be a balance between these conflicting developments. But how can improvements be made when the approved research methodology is limited and measuring instruments to evaluate the luminance (how bright an illuminated surface will appear) of non-static, self-luminous LED displays are unavailable? Only recently in 2018 did the CIE establish a Technical Committee (4–58: Obtrusive Light from Colourful and Dynamic Lighting and its Limitation) [35] to provide guidelines for the implementation and usage of colorful and dynamic lighting in outdoor applications. It aims to limit obtrusive light to allow astronomical observations, support human health, and to protect the nighttime environment. The CIE is also now looking into the development of metrics and suitable methods that will help to limit or prevent obtrusive light from such lighting systems.

The first aim of this research study is to raise awareness about global light pollution in mixed-use developments in large cities from media architecture and non-static LED displays, and to provide an in-depth account of existing global light pollution laws. With such displays becoming more common in urban environments, this material is not only relevant and necessary, it will help shape the future landscape and nightscape of our cities and towns.

Moreover, based on the presented case study of Zurich's Banhofstrasse shopping street, which has experienced an unprecedented 43 fold increase in the installation of video LED displays since 2015, suggestions are proposed on how to improve the existing situation with guidance that contributes new knowledge to the field. The authors also highlight the possible difficulties involved with measuring non-static, self-luminous LED displays with commonly approved and available devices such as a luminance meter and digital reflex camera for luminance photography.

The second aim of this research study is to establish effective design principles that contribute to the development of environmentally sustainable regulations for the design and application of non-static, self-luminous LED advertising. It is not only lighting designers and illuminating engineers who will gain from this research; those involved in the design, planning, and approval process will also benefit. This includes light artists, architects, urban planners, landscape designers, sustainability consultants, biologists, ecologists, and planning officers (representatives of local planning authorities). Last but not least, this research will help improve the enjoyment of cities after dark. This includes improved walkability, navigation and wayfinding in urban spaces, and most importantly, the facilitation of conditions that better support quality sleep for residents, tourists, and visitors alike.

This paper is organized into eight sections. Section 1: demonstrates how the research fits within a larger field of study and highlights why it is important. Section 2: provides definitions and an extensive background study of global approaches to reduce light pollution. Section 3: defines the research hypothesis. Section 4: describes traditional methodologies and new methods and protocols to evaluate the luminance of non-static, self-luminous LED displays. Section 5: provides a precise description and summary of the experimental results. Section 6: discusses the findings and their implications, and explains how they can be interpreted via their perspective of the working hypotheses. Section 7: provides the study's limitations. Finally, Section 8 was added to provide a synthesis of the key points and recommends new areas for future research, as Sections 7 and 8 of the study are long and complex.

2. Background Research

An extensive background study was undertaken for a period of six months. This involved investigating the global approaches to reduce light pollution from media architecture and animated LED displays. Our research consisted of a thorough review of published lighting standards, guidance and policies, books, scientific research papers, reports, and realized case studies, and also involved personal interviews with tram drivers and passersby within in the area researched.

2.1. The Importance of Correct Definitions

When a new field emerges, as in the case of media architecture [36], and when no clear interchangeable definitions are established by professionals that can be commonly adopted by the general public, one ends up with different interpretations and meanings [37]. A definition permits mutual understanding of a topic when a particular subject is discussed and debated. In the context of this paper, in order to fully absorb and understand the content, definitions for the following four terms have been provided: (1) media architecture; (2) non-static LED advertising; (3) visual light clutter; and lastly, (4) light pollution (Table 1).

As more research and knowledge relating to the field of lighting have become available, the definition of media architecture [38] requires an update.

Table 1. An overview of new definitions. Source: authors' elaboration.

Definition	Proposed Description
Media Architecture	Media architecture is a new emerging field within exterior illumination, where dynamic graphics, text, images, and spatial movement are displayed on elements of the built environment, properly integrated within architectural structures and/or buildings within public spaces. Modern digital technologies allow for adaptation and interaction with users. The main function of media architecture is to "communicate specific information" in an active, dynamic, and interactive form via high-quality visual and artistic content. Media facades and digital outdoor media displays that emit light are a vital component of media architecture and the digitalization of cities, forming part of the original and intellectual enrichment of the urban environment with cultural, social, and economic implications for the immediate surroundings. Such installations are usually permanent in nature, but can have variable, temporary content. Well-designed media architecture should not only enhance the environment, it should also be biologically and ecologically responsible, minimizing its impact on the nighttime landscape, and the health and well-being of human residents, wildlife, and/or flora and fauna.
Non-Static LED Advertising	Non-static LED advertising can be defined as a means of promoting just about anything in a publicly or privately owned space. It can also be used commercially for marketing purposes (light art installations). The systems use LEDs and feature different resolutions, colors, luminous intensities, and lighting controls. They can be installed on a temporary or permanent basis, and content can be dynamic or static, in low or high resolution, and in the form of text, images or video sequences. Due to the technological advancements in the development of the brightness of LEDs, such display systems can also be used outdoors during daylight hours. There are different types of digital advertising platforms: signs, logos, lettering, shop windows, screens or media facades [39].
Visual Light Clutter	Visual light clutter in the urban environment at night (Figure 3) is defined by the authors as the state in which too many items lead to a degradation of the performance of a visual task at night. This occurs when the human eye cannot rest, as it is constantly scanning, moving, and absorbing information from an environment with an excess of light sources, coupled with sudden changes in luminance levels and contrast. All of these factors can cause an extreme sense of chaos and disharmony in the urban realm.
Light Pollution	" ... every form of artificial light in the wrong place at the wrong time which creates sky glow, glare, nuisance, and other relevant causes of environmental degradation including some properties of artificial light which emit non-environmentally friendly or inappropriate light" [40]. Typically, light pollution consists of four forms: sky glow, glare, over-lighting, and light trespass.

Today, it is also important to differentiate between media architecture and commercial LED video advertising, which is often inadequately integrated within a building envelope and works as an add-on. Keep in mind that the location of media architecture is usually decided by the architect of a particular building and other consultants in order to eliminate any potential safety conflicts in critical traffic zones, for example, intersections where the increased attention of pedestrians, cyclists, and drivers of cars, buses, trams, and other vehicles is required. To reduce the negative impact on the environment and the health and wellbeing of residents, appropriate design and controls are necessary.

Additionally, high-quality visual and artistic content should be provided and applied by professional designers who also define and set different technical parameters. This may include the appropriate pace (number of frames per minute) to allow enough time for identification and absorption of the communicated message. While media architecture can become a well-known landmark for both tourists and locals alike—it is important to stress that although media architecture can incorporate elements of digital outdoor advertising, LED outdoor advertising is not media architecture per se (Figure 2). Both media architecture and non-static LED display advertising can add to visual light clutter if it is poorly designed (Figure 3).

Interestingly, with time and exposure, some people become "immune" to advertising information and overload, and as a consequence, barely notice advertisements. This questions the overall impact and substantial cost of such marketing modes employed in the late hours of the night.

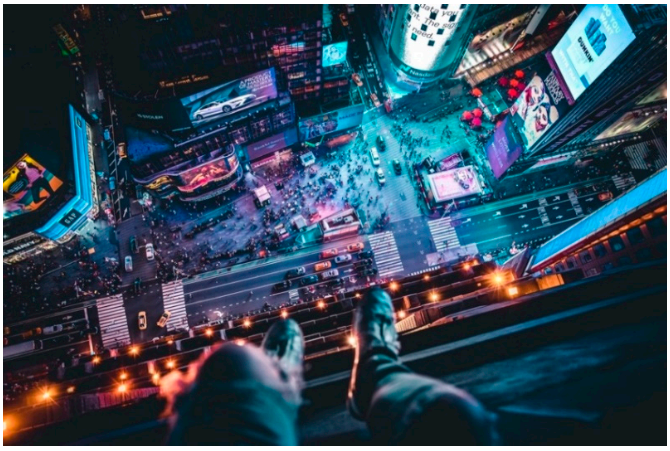


Figure 2. Times Square, New York, US: LED outdoor advertising is not media architecture per se. Source: Andre Benz/Unsplash's figure.

Figure 3. Visual light clutter of Shinjuku—one of Tokyo's business districts at night. Source: Perati Komson/Shutterstock's figure

2.2. Existing Light Pollution Laws, Related Lighting Standards and Guidlines

Recent years have seen issues pertaining to light pollution being acknowledged in both scientific studies [41] and legal consciousness [42]. Even though light pollution presents a major challenge for international lawmakers due to the diversity of its scope, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the International Astronomical Union (IAU) both introduced the autonomous right for every human to transboundary dark-sky landscapes and nocturnal areas. Based on their own legal frameworks, they enforce the responsibility to guarantee that actions do not cause excessive harm to the nighttime environment [40].

To achieve light pollution control at regional and international levels, it is essential to circulate information about it and provide good practice principles for responsible external illumination. The light pollution frameworks that exist in many countries, such as France, Italy, Korea, Slovenia, Spain, and the US, have emerged from multidisciplinary fields of lighting and varied approaches to environmental law. Light pollution has possible negative consequences which breach domestic and international environmental legislation, such as "the right to light pollution control development, the right to a healthful nocturnal environment, mankind's right to a common dark-sky heritage, the right to know the harm caused by light pollution, the duty to carry out light pollution impact assessment, and the duty to adopt effective domestic light pollution law (duty to enforce)" [40].

In 2007, the Slovenian light pollution law, Decree on Limit Values due to Light Pollution of the Environment, was one of the first in Europe. It established specific guidelines for advertisement lighting which limits the electric power of an advertisement surface (W/m^2) as well as the average value of the entire illuminated facade surface to 1 cd/m^2 [43].

In the UK, the Clean Neighbourhoods and Environment Act 2005, makes light nuisance subject to criminal law. It relates to "artificial light emitted from premises so as to be prejudicial to health or a nuisance". This act allows residents to take autonomous action [44].

In the US, both the IDA and the Illuminating Engineering Society of North America (IES) have developed a Model Lighting Ordinance (MLO) to address the need for consistent and stringent outdoor lighting regulation [45]. The MLO outdoor lighting template is intended to support municipalities in developing outdoor lighting standards that reduce glare, light trespass, and sky glow, and its dark-sky protective approach includes the use of five lighting zones to classify land use with appropriate lighting levels for each of the zones. Also, the US Green Building Council (USGBC) via the Leadership in Energy and Environmental Design (LEED) introduced a green building rating system. Their Light Pollution Reduction Credit encourages the reduction of light trespass and sky glow [46], but the main objective of this system is to save energy with lighting installations. For internally illuminated exterior signage, they limit the luminance range to no more than 200 cd/m^2 during nighttime hours and 2000 cd/m^2 during daytime hours [47].

In France in 2013, the Anti-Light Pollution and Energy Consumption Law was introduced by the Ministry of Ecology, Sustainable Development, and Energy. According to this regulatory framework, illuminated advertising signs must be turned off at night, between 01:00 and 06:00, except for at airports and in urban areas with more than 800,000 inhabitants. Surface luminance, energy consumption, and anti-glare devices for digital illuminated advertisements were also defined [48].

In 2012, the Korean Ministry of the Environment passed the Act on the Prevention of Light Pollution Due to Artificial Lighting to reduce severe light pollution brought about by the rapid economic development of the past few decades. This regulation introduced limits on the average luminance and maximal vertical plane illuminance of flashing screen videos based on four environmental zones and the time of application [49].

In Hong Kong, a voluntary initiative established by the Environment Bureau of the Government of the Hong Kong Special Administrative Region called the Charter on External Lighting was put in place. This scheme requires participatory businesses to switch off all external lighting for decoration, promotion or advertising, as well as rooftop signs, from 23:00–07:00. So far, a few thousand companies have participated in this initiative [50]. Sadly, this voluntary scheme only partially reduces light pollution and it will not be effective if the authorities cannot issue warnings or penalties for those who breach the requirements.

The existing European standard EN12464-2:2014, called Light and Lighting—Lighting of Work Places, Part 2: Outdoor Work Places, published by the CIE [51], created requirements to protect the nighttime environment and control the obstructive light from exterior lighting installations on flora, fauna, and humans. Unfortunately, it does not differentiate between screen and sign luminance requirements based on their size (Table 2). This means misinterpretation of the allowed values can occur. Also, the small sign allowance of 1000 cd/m^2 for the high district brightness environmental zone E4 (town/city centers and commercial areas with a high level of nighttime activity) will have less of a negative impact on light pollution and glare, compared to displays that take up the whole window of a shop front on the ground floor, etc., or even an entire facade [51]. In the past, signage was much smaller so its luminance could be higher without impacting the surroundings on a large scale. Over time, however, this changed and there are now large media facades and LED displays that sometimes cover an entire building, yet the recommended luminance values remained the same, without taking into consideration the size of the display. There is also no differentiation in the above lighting standard between static and non-static displays. Additionally, the proposed standard measurement methodology cannot be applied to non-static, self-luminous LED displays, as the measuring tools cannot simply record the values (see Section 4.1.1 for a detailed explanation).

Table 2. Maximum obstructive light permitted for exterior lighting installations. Source: [51].

Environmental Zone	Light on Properties		Luminaire Intensity		Upward Light Ratio	Luminance	
	E_v (lx)		*I* (cd)		R_{UL} (%)	L_b (cd/m^2)	L_s (cd/m^2)
	Pre-Curfew	Post-Curfew	Pre-Curfew	Post-Curfew		Building Facade	Sign
E1	2	0	2500	0	0	0	50
E2	5	1	7500	500	5	5	400
E3	10	2	10,000	1000	15	10	800
E4	25	5	25,000	2500	25	25	1000

E1 represents intrinsically dark areas, such as national parks or protected sites; E2 represents low district brightness areas, such as industrial or residential rural areas; E3 represents medium district brightness areas, such as industrial or residential suburbs; E4 represents high district brightness areas, such as town centres and commercial areas; Ev is the maximum value of vertical illuminance on properties in lx; I is the light intensity of each source in the potentially obtrusive direction in cd; RUL is the proportion of the flux of the luminaire(s) that is emitted above the horizontal, when the luminaire(s) is (are) mounted in its (their) installed position and attitude, and given in %; Lb is the maximum average luminance of the facade of a building in cd/m^2; Ls is the maximum average luminance of signs in cd/m^2.

Another attempt to limit the negative effects of light pollution involved the CIE 150: 2017, the updated document titled the Guide on the Limitation of the Effects of Obstructive Light from Outdoor Lighting Installations [52]. It defines the basis for well-designed external illumination and introduces five different environmental zones (E0–E4) based on their use and location, and different aspects of lighting. The guidance establishes acceptable levels of sky glow, light trespass into windows from a facade, and the permissible maximum average luminance of a facade. It also recommends that facade lighting be switched off completely after 23:00 and remain off until 06:00. Unfortunately, the problems mentioned in the European standard EN12464-2:2014 were not addressed and resolved in this document either.

Also, the Institution of Lighting Professionals (ILP) from the UK created a Professional Lighting Guide PLG 05, called the Brightness of Illuminated Advertisement [53], which provides clear guidance on the maximum recommended luminance level of a sign. For the first time, the luminance of an advertisement display has been introduced in relation to its size (up to 10 and over 10 m^2) for five specific environmental zones. The suggested luminance levels are higher compared to the ANSI/IES RP-39-19 and IDA Guidance recommendations. Also, the proposed standard measurement methodology cannot be applied to non-static, self-luminous LED displays, as the measuring tools cannot simply record the values (see Section 4.1.1 for a detailed explanation).

The recently published IES standard ANSI/IES RP-39-19, Recommended Practice: Off-Roadway Sign Luminance [54], contains restrictions on maximum sign luminance to limit the negative impacts of glare, light trespass, sky glow, animal attraction as well as driver distraction. These requirements are only for the lighting of signs that are not regulated by a federal, state, provincial, or local jurisdiction, and includes on-premise and off-premise, internally and externally illuminated, and electronic signs. For the first time, luminance differentiation has been introduced for daytime and nighttime (Table 3). The sign luminance levels are between 2 to 10 times lower for all environmental zones than the recommended values by CIE. This is an American National standard, thus, it is only applicable in the US.

Still, in spite of any progress made, there is an issue with the measurement methodology as it requires that: "All measurements shall be taken of the sign surface at its maximum level of illuminance". Although subsequent guidance instructs that: "The field of view of the meter used, shall be fully covered by the white or lightest-colored surface of the sign", this is impractical as it might be difficult to achieve these criteria as the available measuring tools cannot record the values (see Section 4.1.1 for a detailed explanation).

Table 3. Maximum sign luminance by lighting zone (cd/m^2). Source: [54].

Lighting Zone	Nighttime	Daytime
LZ0	0	0
LZ1	20	3500
LZ2	40	3500
LZ3	80	3500
LZ4	160	3500

Also, the International Dark-Sky Association (IDA), a globally recognized leading authority that combats light pollution, has played a vital role in protecting the nighttime environment as well as preserving our heritage of dark skies via the promotion of best lighting practices and environmentally responsible outdoor lighting. One of the latest additions to its work is the IDA's Guidance for Electronic Message Centers (EMCs) [55].

This document does not distinguish between on-premise signs and off-premise signs as do the IES standards, nor between signs for advertising versus other uses. It provides minimum requirements and a set of best management practices such as: monitoring, sensitive area setback, distraction limitations, gradual brightness reductions, etc., in order to further decrease the negative impact and reduce the environmental risks of illuminated signage. The recommended luminance levels for night are the same as in ANSI/IES RP-39-19.

Although previous or existing national and international frameworks provide some general guidelines on light pollution control from static advertisement signs, light pollution from media architecture and LED non-static, self-luminous displays has only been partially addressed. This is an important point because they differ substantially, see Table 4. There are a number of reasons for this:

- The rapid development of solid-state lighting: LEDs and lighting control technology has meant this field has just recently emerged, and although it has increased to an unprecedented scale, scant research on its impact has been undertaken and made available;
- While research is being undertaken in chronobiology and other related fields, wider awareness is needed about the non-visual effects of artificial light on the circadian cycle and its negative consequences on humans, flora, and fauna [56]. This crucial study needs to be acknowledged and its outcomes integrated into lighting norms and regulations;
- The mixed use of urban development sets a great challenge due to the conflicting interests of businesses and residents;

- The changing light levels of existing LED video installations make it very difficult to accurately measure their luminance output, and the equipment needed to do this effectively does not exist.
- Lastly, these standards and guidelines are not free of charge.

Table 4. An overview of existing luminance requirements based on current lighting standards and guidelines for mixed-use urban zones. Source: authors' elaboration.

Lighting Standard/ Guidelines	Year Published	Environmental Zone	Luminance at Night (cd/m^2)		Curfew Times
EN12464-2:2014 called Light and Lighting—Lighting of Work Places, Part 2: Outdoor Work Places	2014	E4	25 (Building facade)	1000 (sign)	no
CIE 150: 2017, the Guide on the Limitation of the Effects of Obstructive Light from Outdoor Lighting Installations	2017	E4	25 (Building facade)	1000 (sign)	yes
ILP's Professional Lighting Guide (PLG 05): The Brightness of Illuminated Advertisement	2014	E4	600 (up to 10 m^2 illuminated area)	300 (over 10 m^2 illuminated area)	no
ANSI/IES RP-39-19, Recommended Practice: Off-Roadway Sign Luminance	2019	LZ2	40		no
IDA's Guidance for Electronic Message Centers (EMCs)	2019	LZ2	40		yes

The lack of unified guidelines makes it extremely difficult for local authorities to make educated decisions when it comes to dealing with applications for building permits of this kind. Additionally, in 2016, the document Features of and the Evaluation Criteria for LED Outdoor Advertising, was created in Europe. It was designed to help facilitate application procedures and can be used when submitting written applications to gain permission to install an LED outdoor advertising system [39].

A more accessible global framework should lead to more awareness about the numerous problems caused by light pollution. Where there are threats of serious or irreversible light pollution from media architecture and LED displays, the lack of full scientific certainty should not be used as a reason for postponing such precautionary or preventive approaches. Restrictions on lighting practices must be established whilst creating a sustainable environment for effective energy-related products, environmentally friendly lighting practices, and night environment protection.

2.3. Future Trends in Display Technology

Although LED video displays are still expensive, there has been a notable decrease in price in recent years. Estimates by IHS Markit indicate they will be even more affordable in the near future [57]. This technology already offers intense brightness of screens (greater than the 3000 cd/m^2 suitable for outdoor daytime environments). Their form and size can be custom-made, and the display can have a smooth surface without any frames/bezels to provide an undisturbed image. Lastly, with a narrow, less than 2 mm pixel pitch (NPP), they can provide brighter high-resolution videos. All of the above means we should expect more of this technology in our cities, which, unless properly controlled, will significantly increase light pollution.

3. Research Hypotheses

In order to accomplish the research goals and examine how modern non-static, self-luminous LED displays are significantly increasing problematic light pollution, this study developed the following operational hypothesis:

Hypothesis 1 (H1). *Media architecture and non-static, self-luminous LED displays are increasing urban light pollution due to the uncontrolled levels of excessive vertical luminance, an absence of tools to adequately record and verify the measured data, and a lack of unified lighting design standards that can help to minimize and mitigate the issues.*

4. Materials and Methods

This scientific study involved a mixed-methods research approach to simultaneously collect, analyze, and interpret both quantitative and qualitative data (Table 5), including a Field Measurement Survey (Step 1) and a Photographic Survey (Step 2).

Table 5. An overview of hypotheses and respective qualitative and quantitative methods used for the analysis, based on observed measured phenomena. Source: authors' elaboration.

Hypothesis	Subject Studied	Method
Hypothesis	Urban light pollution	Site-wide photographic survey (to identify over-lighting, light trespass, and discomfort glare impacting visual wellbeing)
		A field measurement survey of nighttime visual luminance (Lv) to verify recommended levels
		Comparison and evaluation of achieved results in relation to literature examples
	Appropriate measuring tools	A field measurement survey of nighttime visual luminance (Lv) with a standard luminance meter
	Design standards and guidelines	Literature review (comparative and critical analysis of current research papers, standards, and technical legislation)

4.1. Field Measurement Survey (Step 1)

This research method was applied to help identify and evaluate the possible exceeded vertical luminance levels of LED displays/illuminated advertisements in the windows on the main shopping street of Banhofstrasse in Zurich, Switzerland (Figure 4). This area was chosen for the following two reasons: (1) in 2004, the City of Zurich established the Plan Lumiere (an urban lighting masterplan) [58] to provide lighting guidelines on an urban scale, but recommendations regarding the illumination of shop windows and advertising are lacking; (2) since 2015, there has been an unprecedented increase in the installation of animated LED displays.

Bahnhofstrasse is one of the world's most expensive shopping streets and it is considered a fine example of an exclusive shopping avenue by other cities in Europe and overseas. In 2018, a study by Cushman and Wakefield [59] named it the fourth most expensive street for retail property in Europe, and the ninth most expensive worldwide. The street is approximately 1.4 km long with shops, banks, coffee houses, restaurants, and hotels located on both sides. It begins with Station Square (Bahnhofplatz) in front of the main Railway Station Building (Zurich Hauptbanhof), passes Paradeplatz, and ends at Lake Zurich with Burkliplatz Paradeplatz adjacent to the street, which is one of the most famous squares in the city, with the main headquarters of two of the largest Swiss banks: Credit Suisse Group and UBS. As this renown street sets a precedent, if rules are established for LED animated advertising, it is very likely the rest of the world will consider them important. Field measurements were conducted in 27 locations.

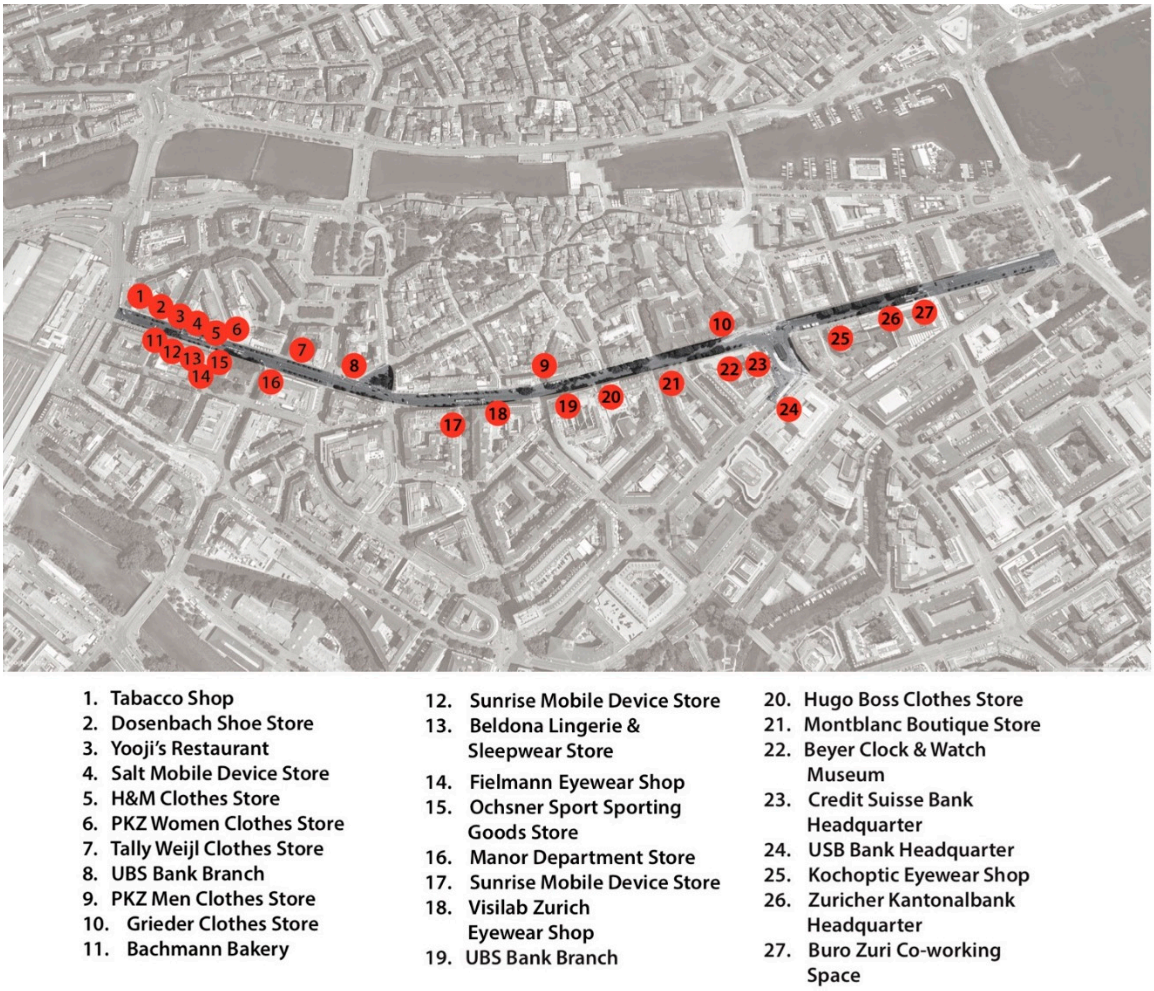


Figure 4. Banhofstrasse, Zurich, Switzerland: an overview of existing locations of LED displays in 2019. Data was estimated from a site-wide survey. Source: authors' figure.

4.1.1. Procedure

A photometric measurement of vertical luminance (L_v) on site was performed in March 2019, in the evening between 20:30 and 22:00 during dry, cloudless weather conditions with the following commonly available tools: (1) a luminance meter, (2) a digital reflex camera for luminance photography, and (3) a new video luminance meter mobile phone application (Figure 5). The measurements were taken as viewed from the point of emission with the measuring cell of the video luminance meter mobile phone application positioned parallel to the display surface.

Figure 5. An example of the results from a typical outdoor luminance measurement in cd/m^2 taken by a video luminance meter mobile phone application with a false color image function for easy evaluation. False color assigns different colors to areas of different luminance exposure in the image. Source: Opticalight's figure.

The measuring device encompassed the whole of the display including parts of its surroundings, and when required, took into account the field of view based on color discrimination perceived by the human eye (Figure 6). Precaution was taken when recording data to ensure no shadow from the person measuring the light produced by the LED display under investigation interfered with the captured data, as this would result in inaccurate results. We first tried to obtain data using standard tools such as a luminance meter (1) and a digital reflex camera for luminance photography (2), but, unfortunately, due to the constant movement of the LED display in both instances, the luminance meter sensor could not focus, and in the case of the digital reflex camera, the obtained frame/picture was significantly delayed so it was not possible to obtain any correct values for L_v. Due to the above reasons, we were unable to use traditional, established, and standardised methods for recording measurements of luminance levels using measurement point grids [60].

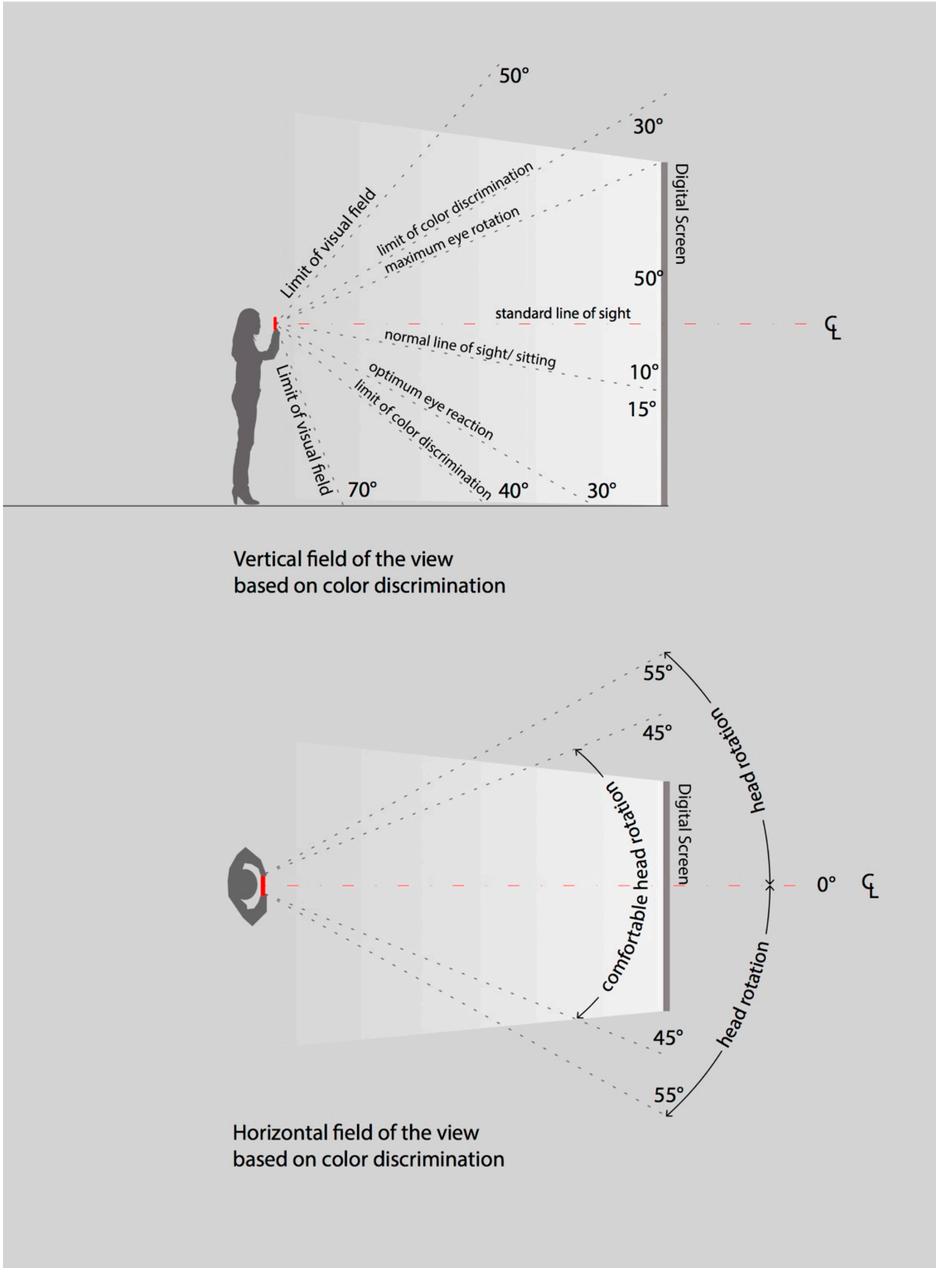


Figure 6. The setup for luminance measurements of non-static LED displays taking into account the vertical and horizontal field of view of color discrimination by the human eye. Source: authors' figure based on Reference [61].

While searching for a solution to our problem, we came across the mobile phone application Candela App which allowed us to obtain false color video recordings with a calibrated candela per square meter spectrum. After a review of the whole recording, we could identify the vertical luminance (L_V) values by stopping the frame Additionally, we could obtain an image as shown in this research. All still images were taken from videos.

The Candela App should be used only as a first step to evaluate if the luminance levels are over the recommended values, based on the CIE EN12464-2:2014 (Table 2) building facade luminance requirements. This helps avoid the unnecessary inconvenience involved with contacting the shop, restaurant or business owner/s and needing to then change the lighting setting just to take measurements as recommended in the ANSI/IES RP-39-19, Recommended Practice: Off-Roadway Sign Luminance document.

4.1.2. Analysis and Hypothesis Testing

Our experimental measurement campaign needed validation by data error analysis (e.g., the calculation of mean, standard deviation, relative percentage error).

Additionally, a scatter plot was used to validate two-dimensional data with dots to represent two different variables—one plotted along the x-axis (number of installations) and the other plotted along the y-axis (luminance values obtained from the outdoor luminance measurements in cd/m^2). This provides a visual reference that reveals how much luminance levels have increased over the permitted amount.

The set up for luminance measurement of non-static LED displays (Figure 5) relates to the visual field geometry of the human eye, which involves a viewer's cone of vision and related viewing angles. When standing, the normal line of sight is approximately 10 degrees below the horizontal [61]. Depending on the particular color, the color starts to disappear between 30 degrees and 60 degrees of line of sight.

4.2. Photographic Survey (Step 2)

A photographic survey was performed which involved taking a nighttime photograph of each LED display to document and record the installation measurements, as well as to evaluate the numerous visual and physical characteristics of the installations.

Procedure

After recording luminance measurements, an image of each display was taken by a digital camera mounted on a tripod and positioned in the plane perpendicular to the line of sight towards the middle of the LED display that encompassed the whole image.

4.3. Technical Equipment

The following professional equipment was used to perform the lighting research (Table 6).

Table 6. Overview of technical equipment used to measure visual luminance (L_V). Source: authors' elaboration.

Category	Company	Model	No. of Items
Luminance Meter	Konica Minolta	LS-100	1
Camera Photometer (Digital Reflex Camera for Luminance Photography)	Techno Team	LMK Mobile air	1
LMK LabSoft software	Techno Team	NA	1
Mobile Phone	Apple	Apple iPhone 5S Operating system iOS	1
Video Luminance Meter Mobile Phone Application (Figure 5)	Opticalight	Candela Smartphone App Version 4.2.1	1
Photo Camera	Canon	Camera reflex Model CANON EOS D100D—DC 18-55 Manual settings (Aperture f/5.6, Shutter Speed 1/25s, ISO 400)	1

5. Results: Hypothesis Testing

In the presented research study, a field measurement survey was carried out to determine the extent of light pollution and the amount of obstructive light produced by non-static, self-luminous LED displays located in the Zurich city center on the main shopping street, with some commercial activities at night. The results are shown in Table 7. They consist of a nighttime photograph of the LED display related to its specific location, and the maximum and minimum values of vertical visual luminance (cd/m^2) of each display. Additionally, the minimum and maximum sizes and display resolutions, and any lighting control observed, were included in the results of the photographic survey evaluation.

5.1. Results: An Overview

Out of 28 measured locations (Table 7), four of the LED displays were broken (location No.: 1, 5, 7, 16), so values of vertical luminance could not be measured. No pre-curfew times were observed, nor were there strict requirements of luminance levels applied to control obstructive light. Also, only one LED display (location No.: 6a) employed a daylight sensor which adjusts the luminance levels to outdoor lighting conditions (luminance increases by day and decreases by night).

Table 7. Banhofstrasse, Zurich, Switzerland: a detailed overview of the results of non-static, self-luminous LED advertisement displays in regard to their location, ownership, the display's nighttime photograph and size, any lighting control used, and its maximum and minimum luminance values. Source: authors' data.

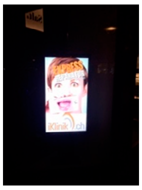
Location on Plan	Business Type/Name	Nighttime Photograph	Display Size	Lighting Control	Maximum/Minimum Vertical Luminance Values [1] (cd/m^2)
1	Tobacco Shop	Broken Display	Broken Display	NA	Broken Display
2	Dosenbach Shoe Store		160 cm × 300 cm 160 cm × 300 cm	no no	375/15
3	Yooji's Restaurant		90 cm × 160 cm	no	30/2
4	Salt Mobile Device Store		60 cm × 100 cm 60 cm × 100 cm	no no	548/31
5	H&M Clothes Store	Broken Display	200 cm × 250 cm	NA	Broken Display

Table 7. *Cont.*

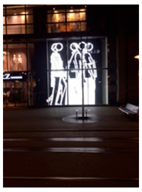
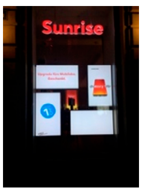
Location on Plan	Business Type/Name	Nighttime Photograph	Display Size	Lighting Control	Maximum/Minimum Vertical Luminance Values [1] (cd/m²)
6a	PKZ Women Clothes Store		720 cm × 720 cm	yes/no	581/2
6b			100 cm × 160 cm		218/8
7	Tally Weijl Clothes Store	Broken Display	150 cm × 160 cm	NA	Broken Display
8	UBS Bank Branch		80 cm × 160 cm 80 cm × 160 cm 80 cm × 160 cm	no	465/20
9	PKZ Men Clothes Store		100 cm × 170 cm 100 cm × 170 cm	no	480/45
10	Grieder Clothes Store		110 cm × 180 cm	no	369/15
11	Bachmann Bakery		200 cm × 300 cm	no	347/3
12	Sunrise Mobile Device Store		100 cm × 50 cm 100 cm × 50 cm 100 cm × 50 cm 100 cm × 50 cm	no	262/1

Table 7. *Cont.*

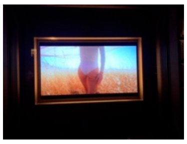
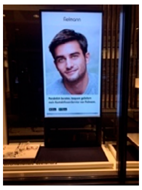
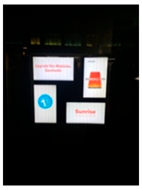
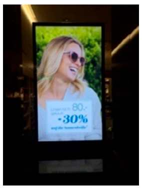
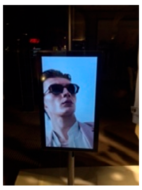
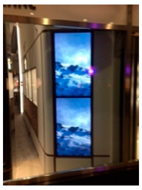
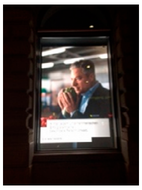
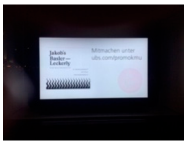
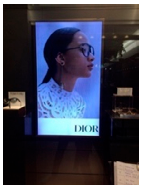
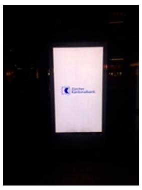
Location on Plan	Business Type/Name	Nighttime Photograph	Display Size	Lighting Control	Maximum/Minimum Vertical Luminance Values [1] (cd/m²)
13	Beldona Lingerie and Sleepwear Store		170 cm × 80 cm	no	1353/20
14	Fielmann Eyewear Shop		70 cm × 120 cm	no	2151/12
15	Ochsner Sport Sporting Goods Store		100 cm × 170 cm	no	195/15
16	Manor Department Store	Broken Display	90 cm × 50 cm	NA	Broken Display
17	Sunrise Mobile Device Store		60 cm × 30 cm 60 cm × 30 cm 60 cm × 30 cm 60 cm × 30 cm	no	190/2
18	Visilab Zurich Eyewear Shop		60 cm × 100 cm	no	443/14
19	UBS Bank Branch		80 cm × 160 cm	no	465/20
20	Hugo Boss Clothes Store		40 cm × 70 cm 40 cm × 70 cm 40 cm × 70 cm	no	112/3

Table 7. *Cont.*

Location on Plan	Business Type/Name	Nighttime Photograph	Display Size	Lighting Control	Maximum/Minimum Vertical Luminance Values [1] (cd/m^2)
21	Montblanc Boutique Store		60 cm × 110 cm 60 cm × 110 cm	no	73/2
22	Beyer Clock and Watch Museum		50 cm × 35 cm	no	334/115
23	Credit Suisse Bank Headquarter		200 cm × 270 cm 200 cm × 270 cm 200 cm × 270 cm 200 cm × 270 cm 200 cm × 270 cm 200 cm × 270 cm 200 cm × 270 cm 200 cm × 270 cm 200 cm × 270 cm	no	308/4
24	USB Bank Headquarter		160 cm × 80 cm 160 cm × 80 cm 160 cm × 80 cm 160 cm × 80 cm 160 cm × 80 cm 160 cm × 80 cm	no	221/8
25	Kochoptic Eyewear Shop		70 cm × 120 cm 70 cm × 120 cm	no	60/3
26	Zuricher Kantonalbank Headquarter		90 cm × 150 cm 90 cm × 150 cm	no	593/21
27	Buro Zuri Co-Working Space		90 cm × 150 cm 90 cm × 150 cm	no	592/21

[1] The maximum and minimum vertical luminance values were obtained from the video recording made with the help of the Candela app.

5.2. Hypothesis 1 (H1)

It is often challenging to address the impact of artificial light at night produced by media architecture and non-static, self-luminous LED displays, as their orientation can make it impractical to shield them. Since traditional approaches are unsuitable, innovative solutions are needed.

5.2.1. The Number of LED Displays versus Achieved Vertical Luminance

The scatterplot shows a moderately strong, negative, non–linear relationship between the number of LED displays and their vertical luminance as observed at some outliers (Figure 7). The majority of businesses displayed one or two LED displays in their shop windows. The highest number of LED displays in one building was nine (Table 7, LED display location No. 23). There were also two data points identified (Table 7, LED display location No. 14 and 13) that are unusually far away from the general pattern. These had the highest vertical luminance values of 2151 cd/m^2 and 1353 cd/m^2, respectively.

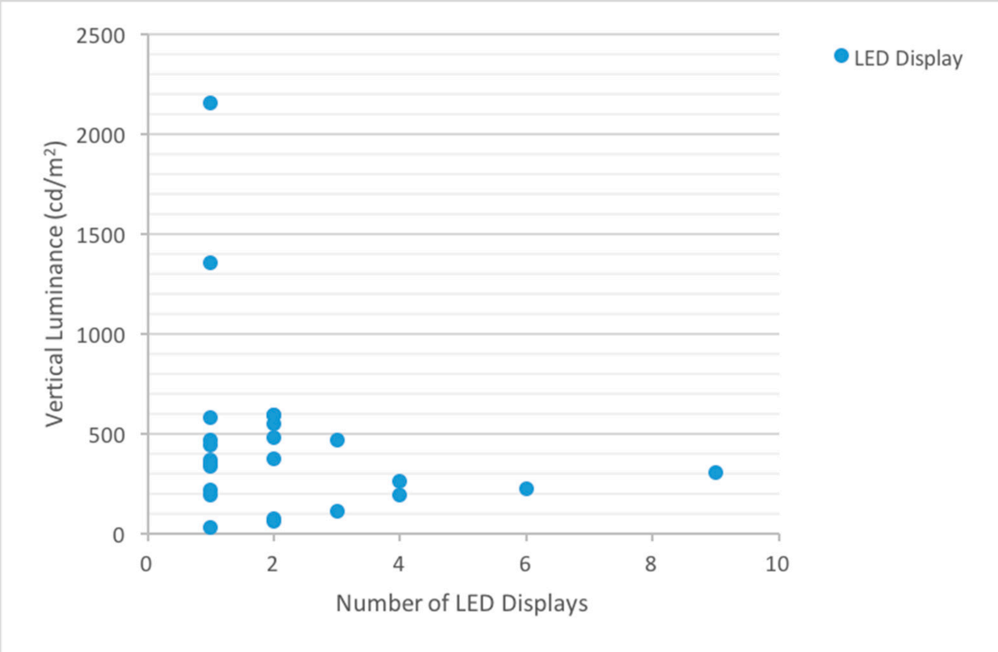


Figure 7. A scatterplot showing the relationship between the maximum achieved vertical luminance and number of LED displays in the year 2019. Source: authors'data.

5.2.2. The Minimum and Maximum Values of Vertical Luminance

The CIE's current 2017 lighting report document Guide of the Limitation of the Effects of Obstructive Light from Outdoor Lighting Installations does not differentiate between static and non-static building facade and sign luminance requirements. Therefore, the maximum permitted values of the building facade luminance for the environmental zone E4 (high district brightness of city center) based on the criterion of light pollution prevention of 25 cd/m^2, was taken as a base for the evaluation of measured outcomes.

We realized that it was not possible to establish maximum permitted values of average surface luminance for non-static, self-luminous lighting installations due to the constant changes in luminance levels with standard measuring tools, so a new measuring tool had to be employed to achieve levels that could be verified.

The obtained mean of luminance for all 28 measured LED displays was 384.46 (Figure 8), with a standard deviation (DS) describing the amount of variability of a set of luminance data values of 446.50 and a standard error of the mean (SDM) of 84.38111894. Bearing in mind that 25 cd/m^2 is the maximum facade luminance limit to minimize urban light pollution, the results indicated that the values we obtained in our empirical research exceeded the permissible standards between 12 and 18 times, considering the standard error. These results confirmed our hypothesis that self-luminous LED displays have a substantial impact, increasing urban light pollution due to the uncontrolled levels of excessive vertical luminance.

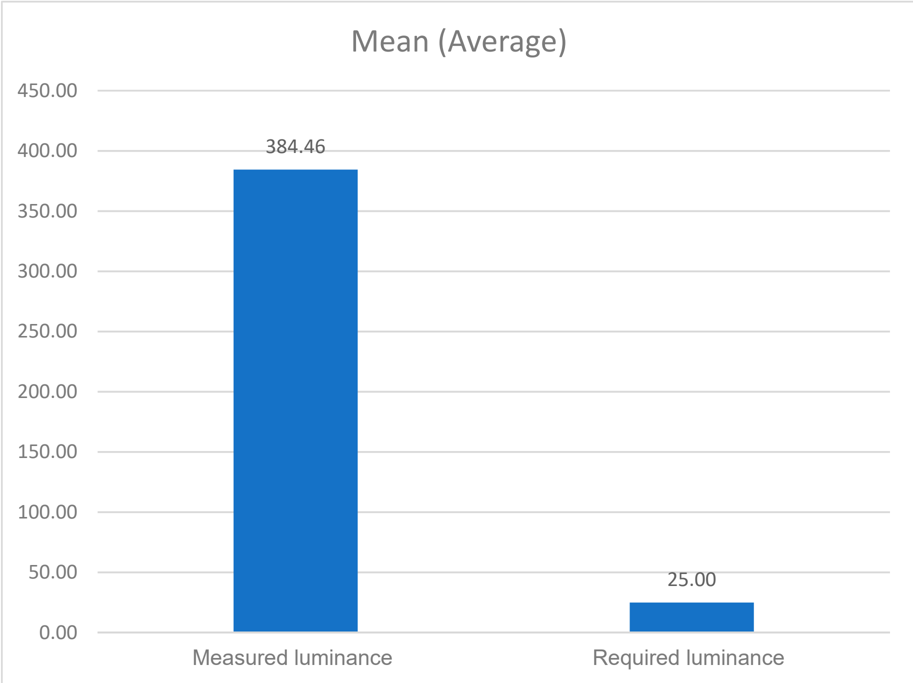


Figure 8. Mean (average) of luminance for all 28 measured LED displays. Source: authors' data.

The recorded vertical luminance values of 30 cd/m^2 from the LED display (Table 7, location No. 3) seemed to be visually the least disturbing to passive recipients as they walked very close by (Figure 9). This was a 0.2 fold increase of the recommended level by the CIE, and a 1.3 fold increase of that recommended by the IES. Whereas, the recorded values of 2151 cd/m^2 from the animated LED display (Table 7, location No. 14) appeared to be the most visually disturbing to passive recipients (Figure 10), as this display showed an 85 fold increase in the level of luminance recommended by the CIE, and a 53 fold increase of that recommended by the IES.

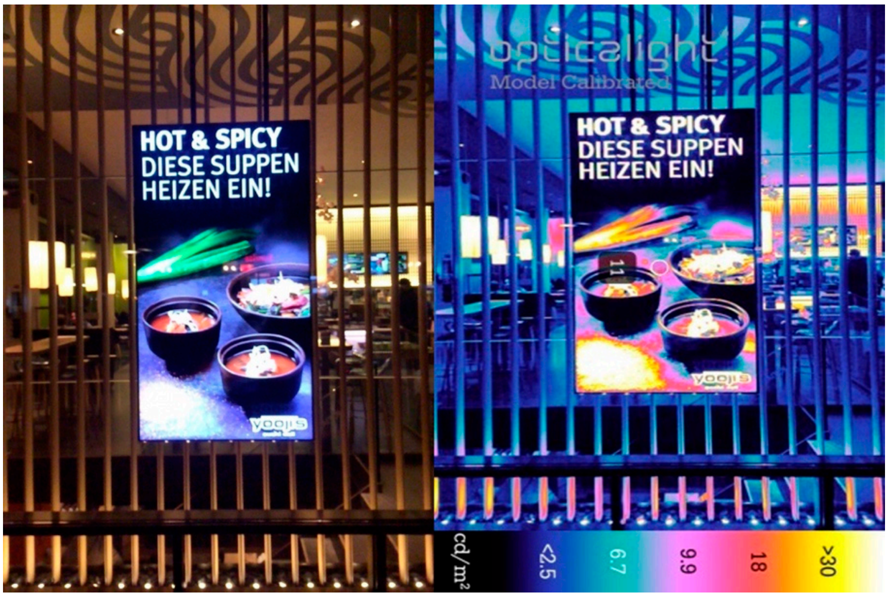


Figure 9. Yooji's Restaurant on Bahnhofstrasse in Zurich, Switzerland, had the lowest luminance distribution in the field of vision, which provides comfortable eye adaptation. It also had a low level of brightness relative to its urban surrounding, with a slow pace of changing frames of moving video images. Source: authors' figure.

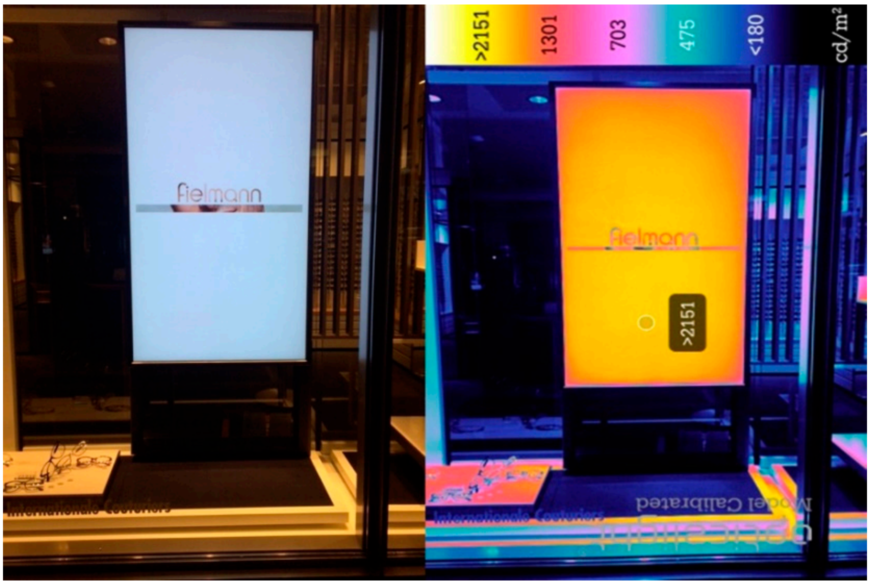


Figure 10. Fielmann Eyewear Shop on Bahnhofstrasse in Zurich, Switzerland, had the highest luminance distribution in the field of vision, uncomfortable eye adaptation due to its high level of brightness relative to its urban surrounding, and a fast pace of changing frames of moving video images. Source: authors' figure.

The excessive luminance of LED screens can also create disability glare which temporarily impairs vision and creates visual discomfort due to the high contrast between the LED screen and the darker surroundings. It can also damage retinal tissue due to the phototoxic effects of shorter blue wavelengths of light emitted by LED technology.

5.2.3. The Minimum and Maximum Sizes of the LED Display

The minimum LED display size of 1.75 m^2 (location No. 22) was 30 fold smaller than the maximum size LED display (Table 7, location No.: 6a) which spans a total area of approximately 50 m^2 and extends over two building stores. Due to the size and brightness of this LED display No. 6a, it generates significant light trespass into the nearby windows of residential flats and a hotel. Additionally, users of the adjacent road are constantly exposed to glare (Figure 11). This lighting installation reduces the ability to see essential information needed to safely navigate the path of travel. Based on the ILP PLG 05 document and display size, the luminance levels are almost twice the permitted 300 cd/m^2 value. The CIE, IES, and IDA have no recommendations that limit the luminance levels in regard to the size of an LED display.

Figure 11. The "Walk" LED light art installation integrated into the facade of the PKZ Woman store on Bahnhofstrasse in Zurich, Switzerland. This was the largest of all the measured LED animated facade displays, and the disability glare it produces has a definite impact on traffic, negatively affecting tram drivers. Source: Julia Hartmann's figure.

5.2.4. The Resolution of LED Displays

The majority of LED displays were high-resolution pixel pitch TV screens, known as video wall or digital signage, with only one exception (Figure 12) of an LED screen with a low pixel pitch of 30 by 30 mm (Table 7, location No.: 6a).

Figure 12. The "Walk" LED light art installation is integrated into the facade of the PKZ Woman store on Bahnhofstrasse in Zurich, Switzerland. The LED screen has a low pixel pitch of 30 by 30 mm. Source: Julia Hartmann's figure

6. Discussion

The main research goal of this study was to provide an overview of the observed vertical luminance produced by LED displays from shop windows. An additional aim was to create appropriate and practical recommendations when applying media architecture and non-static, self-luminous LED displays in mix-use urban developments.

The results of field measurements and a photographic survey support the hypothesis, and they highlight why media architecture and non-static, self-luminous LED displays are increasing urban light pollution due to the uncontrolled levels of excessive vertical luminance. The highest luminance value recorded was 2151 cd/m^2 which was 86 fold higher than the prescribed building facade luminance of 25 cd/m^2. Many other measured on-site LED displays had much higher luminance levels than permitted. Such displays have a greater impact than a small sign or signage mounted on a building, as larger-sized LED displays often fill the whole shop window. Therefore, the luminance values should be much lower and correspond to the display size area. One option could be defining an electric power allowance for advertising surface (W/m^2).

Also, there is an interesting situation observed in Banhofstrasse. Namely, the street seems to be divided into two visually dissimilar areas at night with cheaper high street retail chains closer to the railway station, and expensive high-end designer fashion stores towards the lake. The first group of retailers commonly employ non-static, self-luminous LED displays to attract the attention of younger viewers/passersby who and are drawn to action and novelty, opposite to the second retailer group, which target much wealthier, mature consumers who prefer uniqueness and quality. The bold, colorful, and fast-paced animated displays of the cheaper chain stores do not align with the high-end style of the street.

Furthermore, banks seem to favor large LED video displays that have consistent brightness and content. They appear to use a standard factory setting of 500–700 cd/m^2 acceptable for daytime, but they need be lowered during the night by a considerable degree (existing programmable LED technology already allows for this.)

This study establishes the relationship between increased light pollution from non-static LED displays and a lack of proper design standards and guidelines that can help to minimize and mitigate the issue. The authors propose practical recommendations (Table 8) to help reduce light pollution and the negative impact of obstructive light on human health and wellbeing, traffic safety, and the natural environment.

Table 8. Practical recommendations for LED displays to reduce light pollution and its impact. Source: authors'elaboration.

Impact On	Proposal for Improvement
Human Health and Wellbeing (Residents/Building Occupiers, Visitors, Tourists)	• Question the impact of large LED displays in relatively narrow streets as their viewing will be compromised and the light trespass they create is likely to be problematic. • If an LED display on a building facade is located in a residential area, it should be no brighter than the illuminations on nearby streets, buildings, and squares that operate during agreed curfew times. A screen visibility study should be performed. • The luminance levels of LED displays at night should be lowered to accommodate mesopic and scotopic vision. • Allow curfew times. Ideally, all LED displays should be switched off at the latest by 22:00 in winter and midnight in summer. Exemptions may be possible for agreed special events, celebrations, and nominated areas. • Reduce, or ideally, avoid LED displays that emit blue-rich light (460–500 nm) and vibrantly colored light at night, as this can have a profoundly negative effect on the biology of living organisms. • Place more importance on the colour spectrum or spectral power distribution (SPD) of a display than its Correlated Color Temperature (CCT), as this provides important information about the specific wavelengths of light that are emitted. Choose LEDs with the most appropriate SPD possible. • The CCT of light used in LED displays at night should not exceed 2700 K as recommended by the American Medical Association in Guidance to Reduce Harm from High Intensity Street Lights [62].

Table 8. *Cont.*

Impact On	Proposal for Improvement
Natural Environment	• Assess ambient brightness conditions before beginning to work on any design and its specification, as these are complex issues. The authors cannot emphasize enough how vital it is to use the services of professional lighting designers who prioritize nocturnal placemaking and the reduction of light pollution. • Always ensure that an LED display is thoughtfully integrated into the surrounding architecture and that it fits into and aligns with the context of its urban setting. • Define the environmental zone where each project is located so that the display does not exceed the permitted level of sky glow, light intrusion into windows, and building luminance, etc. • Avoid placing LED displays in residential and recreational areas near urban parks. • Follow best practices and guidelines to minimize sky glow, light trespass, glare, and excess luminance by adhering to the 2019 International Dark-Sky Association Guidance for Electronic Message Centers (EMCs), as well as the Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations from the Commission Internationale de l'Eclairage (CIE) released in 2017. • Limit the excessive luminance of LED displays based on the urban planning zoning for outdoor lighting control. First, define the land-use zone where the LED display is located, and based on this information, assign the appropriate levels. • Provide lighting scene settings integrated with LED displays according to the time of the day/night, day of the week, season, and weather. For instance, rain, mist, fog, and snow will all worsen glare and increase light pollution. • Integrate automatic controls to reduce the light output of installations between daytime and nighttime, and use sensors and/or time clock facilities. • Allow curfew times. Ideally, all LED displays should be switched off at the latest by 22:00 in winter and midnight in summer. Exemptions may be made for agreed special events, celebrations, and nominated areas. • Question the impact of large LED displays in relatively narrow streets, as their viewing will be compromised and light trespass is likely to be a problem. • Apply special louvres and baffles on an LED display to control light distribution and adjust the angle of light emitted from LED boards to reduce upward light spill into the atmosphere, prevent glare from direct view, and minimize light trespass. • Avoid installing LED displays and digital billboards that generate electromagnetic interference as this negatively impacts the performance of cellphones, aviation towers, pacemakers, etc. • Limit the specification of large coverage areas/size of LED displays. • Consider using dark materials for pavement surfaces around the installation as the light emitted from LED displays can bounce off the ground back up into the atmosphere to worsen sky glow. Keep in mind that brighter surfaces will reflect more light.

Table 8. *Cont.*

Impact On	Proposal for Improvement
Traffic Situation/Transport System Users (Motorists, Cyclists, Pedestrians, etc.)	• Avoid placing LED displays near junctions, intersections, pedestrian crossings, and between pedestrians and vehicles where increased attention is required. An LED display should not compete with streetlights or traffic signals/lights. • Ensure LED displays do not flicker as this can be a source of light nuisance. It can also produce disturbing stroboscopic effects, such as trails of lights that can confuse pedestrians, cyclists, and/or vehicle drivers. • Consider the appropriate number of frames per seconds/minutes of the LED display content to avoid hectic movement of images/videos. This can disturb pedestrians, compromise their safety, and distract drivers, resulting in traffic accidents. Flicker can also trigger migraines and cause disorientation and discomfort. • Avoid sudden changes in luminance levels of the LED display, as this can also distract drivers, pedestrians, and cyclists.

As explained in Section 5, it is very difficult to accurately measure and evaluate vertical luminance from non-static, self-luminous LED displays because of the limitations of commonly used instruments, so often values are incorrect. For these reasons, a five-step process (Table 9) is proposed until new approved CIE measuring procedures are introduced. The proposed approach can be applied to any similar cases and/or conditions.

Table 9. Overview of the five-step proposed measurement method for non-static LED displays. Source: authors' elaboration.

Step	Category	Description
Step 1	Pre-Analysis with Candela Application	The authors propose the use of the Candela mobile phone application, (which operates on iOS devices such as iPhones and iPads) to help identify and evaluate possible exceeded luminance levels on site from non-static LED displays [63]. With the application, it is possible to record both surface and point measurements to determine the luminance outcome in cd/m^2. The app will also display a 2D image in a false color rendering presentation with value ranges and definable color gradients. The app is calibrated for use at 10–1000 cd/m^2, 3000 K with reliable precision. Accuracies of up to 10% are achieved depending on calibration status. By comparison, the human eye barely recognizes brightness differences when the light intensity is doubled. This makes the app a valuable tool for pre-analysis. It achieves sufficient accuracy as a design aid, but cannot be used for the verification of legally prescribed measured values. The application is free of charge and it can be relied on as a luminance meter on the go, for identifying any potential light nuisance. At least 5 individual measurements must be made and they need to be averaged.
Step 2	Data Evaluation	After obtaining the luminance data, compare them with the allowed values. If they exceed them, move to step 3.
Step 3	Gathering Measurements that Involve Municipality and Owners/Vendors	Contact your local municipality and request that the vendor/owner allow proper measurements to be taken of the non-static LED displays concerned.

Table 9. *Cont.*

Step	Category	Description
Step 4	Proper Analysis with Standard Luminance Meter	Perform the measurement by stopping the installation on a static image. The screen needs to be turned to the programmed night output white light (RGB) setting, and luminance values are to be measured with a standard luminance meter based on IDA recommendations [55]. For more information on the device and its calibration, refer to CIE ISO/CIE 19476:2014 Standard [64]. At least 5 individual measurements must be made and they need to be averaged.
Step 5	Take Actions	Propose new values for luminance levels as well as the application of sensors and timeclock facilities to allow for changes in luminance levels according to the time of the day. Luminance measurements to be taken: • 1 h after sunset or 1 h before sunrise (use the official daily sunset and sunrise time). • Take measurements in dry, cloudless weather conditions. Rainy, foggy, snowy conditions are prohibited. • Take measurements as viewed from the point of emission. • The measuring cell of the device needs to be parallel to the reference surface, and preferably mounted on a tripod to avoid discrepancies caused by movement. • The distance between the measured non-static LED displays and luminance meter should be such that it will encompass the whole of the non-static LED displays installation along with its surrounds. • Take images to document and record the installation measurements as well as the condition of the installation.

7. Limitations of the Study

Despite the contributions mentioned in Section 6, the study has its limitations which are identified in three areas.

7.1. Research Methodology

- There is a lack of a recommended and approved worldwide research methodology and procedures to measure non-static, self-luminous LED displays.
- No guidance exists for the maximum, minimum, and average luminance of vertical displays, nor are the values from non-static, self-luminous displays assigned to any of the five environmental zones.
- No proposals exist for the spectral emissions of LED light sources.
- No proposals exist for the maximum permitted levels of Upward Light Ratio (ULR) of the installation and vertical illuminance on properties to evaluate the impact of obstructive light.
- It is often impractical to measure the vertical luminance values of a window display as proposed by the IES,—by pausing the video of an LED display to achieve a static image with 100% output of white light (RGB) as typical of the factory setting (it might require a number of approvals and agreements from third parties, access to the interior control room, as well as access to the computer/laptop that has the programmed settings).
- There are still unresolved issues with the measuring tools (for static and non-static LED displays). The calibration of photometers is still performed using incandescent-based standards [65], as there is not a single spectral power distribution that would be representative of all white LED sources. This issue also includes the mobile phone Candela App (from Opticalight) used in this research, which was calibrated to a CCT of 3000 K (warm white light) as a base.

7.2. Tools to Correctly Measure Vertical Luminace of Non-Static, Self-Luminous LED Displays

- The tools typically used to measure the surface luminance of LED displays, like a luminance meter (from Konica Minolta_LS-110 [66]) or portable Imaging Photometer Measurement Systems based on a digital camera photometer (from Technoteam LMK [67]) are limited and insufficient to measure LED displays due to the fact that they have a non-uniform diffusing surface, and a standard luminance meter's sensor is unable to focus on one point, as the luminance levels constantly change, so values are often inaccurate.
- Other measuring tools currently available on the market, such as the calibrated mobile phone Candela App from Opticalight [68], used in this research, or the video luminance meter Elf System from Korean Hi-Land [69], have not been officially approved by the CIE or IES.
- The calibrated free of charge Candela App (from Opticalight) is only available for the following devices: iPhone 4S, iPhone 5, iPhone 5C, iPhone 5S, iPhone 6, iPhone SE, iPad 3, iPad 4, iPad air, iPad air 2, iPad mini, iPad mini 2.
- The CIE recommends taking a minimum of nine readings, but each time the values may still be different (See Section 5.2.2).
- The calculation method procedure for the interpolation of photometric data used by the mobile application might vary from other methods used with different measuring instruments, so comparing values might not provide the same results. According to CIE: "even with the use of high quality instruments, errors of up to 10% due to instrument calibration alone must be expected" [52].

7.3. Field Measurement Survey Setup

- The photocell of the measuring instrument may not have been correctly positioned and aligned with respect to the measured plane.
- With the available measuring tools, it is not possible to completely remove stray ambient lighting (downlights above the screen, luminaires in the background of the store, or input from facade or street lighting), and this may have an additional impact on the overall levels of recorded vertical luminance.
- The field of view based on color discrimination perceived by the human eye is often overlooked and it might be different than the field of view of the luminance meter used, therefore, guidance here is necessary.

8. Conclusions

The increasing use of artificial lighting for advertisement and their energy demands in urban settings require sustainable solutions to mitigate their impact on the environment and climate change.

Even though researchers were calling for action in 2009 [70] to ensure the sustainable implementation and integration of media screens in the built environment, since then, very little has happened regarding research that engages planning systems with the development of appropriate strategies to minimize light pollution. We believe this is due to the fact that there is an immense gap between academia and praxis. Practitioners, societies, associations, and policy makers are generally unaware of the existing body of research and the necessary call(s) for action. We see a huge future opportunity to address this by applying the action research method linking research with professional practice.

Without sufficient research and commonly unified and effective regulations and polices for outdoor lighting practice, light pollution is highly likely to increase globally in the near future (Figure 13). It is, therefore, critical to monitor the fast development and application of media architecture and non-static LED displays every few years, and to establish and/or update any guidelines and standards related to their control.

Figure 13. The Hong Kong skyline at night. Without sufficient guidance, know-how, and regulations, light pollution is highly likely to increase globally in the near future. Source: SCMP's figure.

Our research also reveals that improved measuring instruments, methodology, and technical references are required for the collection of error-free, comprehensive data. Additionally, new lighting performance standards for media architecture and static and non-static LED displays need to be developed. Many cities and towns have never had to handle the environmental impact of these items until recently. This is due to the fact that public concern over the negative consequences of Artificial Light at Night (ALAN) has risen [71,72]. The authors propose that the simplest solution to help reduce their environmental impact in terms of sky glow, light trespass, and glare involves the following: the planning permission for LED display application and their vertical luminance must take into consideration their location/position on the building vertically (crone/roof, middle part, and perimeter) as well as the allowed maximum upper limit of the total surface of a building's facade. If the above is not defined, luminance levels will continue to increase due to the unhealthy and unrestrained competition between advertising brands/investors—and as a consequence, light pollution will drastically worsen.

The presented research makes a novel contribution to literature about non-static, self-luminous LED displays. This is the first time such a detailed overview has been conducted on existing lighting standards and guidelines to reduce light pollution generated by non-static, self-luminous displays. It is anticipated that this practice-based study will help guide the development and implementation of these elements for improved illumination in outdoor urban environments in the future.

Moreover, this study, demonstrates further research is required to more fully understand the relationship between media architecture, advertisement, and healthy nocturnal placemaking in our cities. There should be guidance about the responsible use of light, as well as transparency about the risks of light pollution so residents can make better-informed choices. A careful balance must also be established between the following factors: protecting people's health and life quality, energy savings, the visual creativity of designers, and the profits of business and the LED video display industry.

All of the above recommendations play a role in the sustainability of cities; therefore, four steps have been proposed to enable their implementation: (1) the integration of the proposed guidelines and standards into construction regulations and zoning that controls the location and use of certain types of buildings and spaces within a city; (2) the availability and easy, free of charge access to guidance and best practice document(s) for investors, developers, and design professionals; (3) the establishment of useful, consistent, and predictable frameworks for municipal authorities to grant construction permits and appraisals or to reject construction proposals; (4) the application of Post Occupancy Evaluation (POE) methodology as part of Evidence-Based Design (EBD) by experts as a crucial process to evaluate the impact of existing outdoor media architecture/animated LED displays in order to avoid errors of the past and promote good design examples.

This study also suggests it is necessary to provide supportive scientific literature which is currently lacking in the field of display technologies and media architecture.

Lastly, establishing professional guidance and expertise is essential. Considering the complexities involved, it is key that measurements of lighting installation parameters for non-static LED displays in mixed-use urban environments are taken by professionally qualified people so the results are credible and verifiable.

We do hope that, thanks to this research, the CIE and IES will update their standards in terms of definitions, requirements, and measurement for non-static, self-luminous LED displays located behind a building's glass windows.

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