Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: Jingchun Shen *et al* 2023 *J. Phys.: Conf. Ser.* **2654** 012139

A Critical Review of Lighting Design and Asset Management Strategies. Illuminating Practices and Lessons Learned for Swedish Public Libraries

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Abstract: Most lighting is only designed to meet the visual needs in most public library environments in Sweden. Although lighting-related impacts are relevant to six Unite Nations sustainability goals, some important lighting considerations, such as circadian phase disruption, mode and productivity impact, and energy-efficient operation, are missing in current lighting operating practices. Moreover, most of the current lighting asset management practice in public buildings remains “fix it if only it breaks”. With respect to people-centric health factors, visual index, and lighting asset energy-efficient operation, this study sublimates lighting into a new perspective. Finally, the suggested comprehensive lighting operating strategies integrating digital twins can help designers and operators in defining the optimal design/control strategy in public-built environments, like public library. Digital twin-based decision-making is expected to be applied to lighting design and control in public spaces that improves visual acuity and comfort, positively impact mood and productivity, and provides recommendations on engagement principles under Environment Social Governance (ESG) framework to asset manager/operators.

1. Introduction

Currently, the post covid world faces multiple challenges for buildings, particularly those ones with open access. These challenges posed by climate change, resource scarcity, demographic shift and the increasing demand for buildings supporting human health, well-being and productivity [1],[2],[3],[4],[5] are very relevant to the lighting topic. In the meantime, lighting has become a common building facility that has undergone highly disruptive technology transitions in recent decades. These enormous changes started with the wide development of light emitting diodes (LEDs), which resulted in a rapid and revolutionary replacement of the conventional light sources around our daily life. From another aspect, it accordingly pushes the systematic change from individual lighting source products towards the intelligent lighting systems solution, coupled with the digital platform [6].

Contrary to the substantial changes in the lighting industry, the random site visit to public libraries in Sweden reveals a very different situation. Currently, most lighting design consists of replacing the broken light source with LEDs, and most light asset management practices are based on "fix it if it breaks at all costs", shown in Figure 1.

Figure 1 Site visits to public libraries in Högskolan Darlarna Borlänge campus and Falun campus, and Stockholms stadsbibliotek

With respect to optimizing the substantial potential related to lighting in the public libraries, this study aims to critically review lighting from three perspectives: 1) design strategies; 2) asset management; and its future with 3) digital twin technology.

2. Methodology

The study utilized scoping reviews with a methodology structure illustrated in Figure 2 with main findings from Table 1 . Two broad research questions were defined to identify relevant comprehensive literature for review. To ensure a comprehensive understanding, the authors used the relevance ranking provided by both Web of Science and Scopus. Text similarity between keyword inputs, abstracts, and full-text articles from article metadata were screened to determine relevance ranking from the data sources. Due to page restrictions in this conference paper, only the top 5 influential works on the topic within the past 5 years were included in this paper. Key information was extracted, and common themes were identified by synthesizing the information to develop a critical perspective on the topic. The key findings from the synthesized themes were summarized, and critical perspectives on the topic were provided. Finally, gaps in the literature or areas for future research were identified.

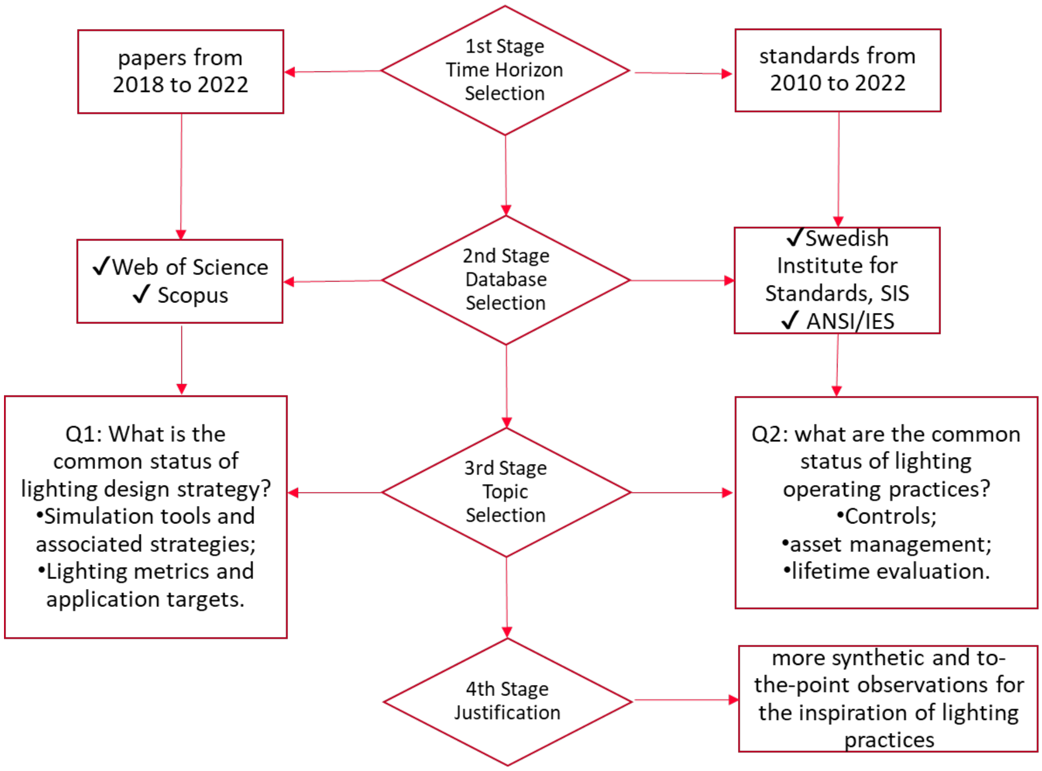

Figure 2 Structured literature review methodology in this study

Table 1 Overview of the reviewed sources

	Ref.	Year	Purpose	Summary Points
Lighting design strategies	[1]	2019	Development of computational framework to improve prediction accuracy of conventional building performance models, including the use of an artificial neural network and feature ranking technique	Framework also has capability to rank the influence of factors impacting human-building interactions.
	[4]	2019	Proposal of agent-based model to simulate occupants' behavior in a building and their indoor comfort together with lighting purposes	Suitable for early stage building studies post-Covid, includes both individual agents and social interaction.
	[7]	2018	Study on popular simulation tools for artificial lighting simulation with associated parameters	Lighting simulation studies have grown considerably since 2010, with around 70% of reviewed articles investigating multiple objective functions and a large majority focused on energy. Top three singly used simulation tools were MATLAB, EnergyPlus, and DOE, while top three for feature enhancements were EnergyPlus/Radiance, EnergyPlus/MATLAB, and MATLAB/LABVIEW.

[8–11]	2022-2023	Latest examples of lighting design research using Rhino and its-based plugins	Growing trend towards use of 3D modelling software for lighting design research, specifically Rhino and its-based plugins. These are based on the RADIANCE engine and have similar features that enhance the understanding of how the built environment interacts with the surrounding climate and enable the optimization of lighting design for energy efficiency, environmental sustainability, and human factors such as visual comfort, circadian rhythm, and well-being.
[12]	2019	Development of general rationalization algorithm for redesigned lighting using simulation models for daylighting, artificial lighting, and mixed lighting	Algorithm validated with practical measurements and creation of digital twin in simulation tool.
[13]	2020	Proposal of framework to automate process sustainability assessment for proposed buildings, integrating BIM and LEED certification system	Optimizes credits a building could potentially earn at the conceptual stage.
[14]	2020	Proposal of synthetic-real interaction training strategy for deep networks as a technique for visual quality improvement	Synthesizes low-light image pairs by treating depth map as illumination, avoids designing complex regularization losses.
[15]	2021	Updated lighting standards to improve design and energy efficiency	The EN 12464-1:2021 standard updates the EN 12464-1:2011 standard and addresses issues raised from minimum requirements and missing key details. The changes include defining design areas with relevant requirements, considering maintenance factors in recommended illuminance values, and additional considerations of lighting control, energy, and cost.
[16]	2021	Technical specification of BIM Properties for lighting - Luminaires and sensing devices	The technical specification assists in making informed decisions during the design, construction, and operation phases of a building project. Contributions of this technical specification are illustrated in Figure 2.
[17]	2022	Find 3 mechanisms for lighting energy savings goal	Seo and Yun identified three mechanisms for achieving lighting energy savings: improving efficiency with light source replacement, adjusting illuminance level with lowering luminaire output, and reducing surplus consumption with a control system.
[12,18,19]	2019, 2021,2022	Parametric study on lighting retrofits in existing building	Facades and roofs should incorporate active and passive strategies to achieve this goal. Natural lighting optimization strategies include building orientation and form, atrium elements, and geometric factors.
[20]	2021	Provide guidance on optimum Window-Wall-Ratio (WWR)	Albatayneh et al. provided guidance on the optimum WWR for energy-efficient buildings in Jordan. The typical WWR in Jordan with efficient LED lighting could be lower than the highest WWR stipulated by ASHRAE standards.

	[21]	2018	Assess energy efficiency of climate-smart lighting management	Acosta et al. used dynamic metrics to assess the energy efficiency of climate-smart lighting management and its impact on economic profitability. Dynamic metrics are derived from involved variables such as weather conditions, occupancy hours, and illuminance thresholds.
	[2]	2018	Investigate the impact of human factors on retail lighting design	Yilmaz investigated the impact of human factors on retail lighting design, establishing a connection between luminous environment perception, price perception, and quality perception of displayed products.
	[22]	2022	Create an ergonomic rationalization algorithm for lighting design	Dupláková et al. described the creation of an ergonomic rationalization algorithm for lighting design in a working environment using simulation tools to simulate, evaluate, or rationalize physical loads, physical factors of the working environment, or risks at the workplace.
	[7]	2018	List control systems associated with lighting systems	Fuzzy logic and MAST were most prevalent, while conventional ON/OFF was just one instance
	[15]	2021	Discuss the importance and types of smart lighting control systems	The Standard lists several implement purposes that an adjustable system ensures: 1) To maximize available daylight; 2) To consider occupancy of the space; 3) To cater for changes in visual tasks, occupant's preferences or needs.
	[6, 17, 21,23, 24,25, 26]	N/A	List most common lighting control systems	1) Present a variety of lighting control system on the market; 2) Highlight importance of control grouping for building managers; 3) Indicate the future tendency in lighting control based on data collecting.
Lighting asset management	[5]	2022	Propose an asset-management model addressing challenges for regulators, managers, and operators of public-lighting systems	The model is based on the normal distribution function and can help with the management of public lighting systems
	[3]	2020	Propose a smart building light management system connected with the internet of things (IoT) featured lighting devices and its realization of human-centric lighting (HCL) control	The system uses advanced computer vision techniques to regulate objective human-specific lighting devices
	[6]	2017	Show the latest lighting product developments	It will lead to novel applications in building asset management, such as Light Fidelity (LiFi, instead of WiFi), indoor positioning, light as a service or light leasing
	[27]	2021	Evaluate an intelligent lighting system within the whole process of emergency management in the subway to achieve a rapid and effective response	Lighting is an essential element of emergency process management in public areas
	[28]	2020	Present an example within the framework of the Public Energy Living Lab (PELL) initiative launched by ENEA	The PELL platform aims to collect all the structural and electric measurements of public lighting plants to evaluate their performances and functionalities
	[25]	2019	Highlight the critical components of a model "Smart and Digital Green Educational Campus" through IoT technology	The model can help transform educational campuses into smart and sustainable ones

[29]	2015	Study the impact of annual growth in public lighting on the failure rate of lighting lamps	The failure rate of lighting lamps increases with the expansion of the public lighting network, but the failure rate associated with the initial extension is constant
[5]	2020	Assess lighting services from an Environmental, Social, and Corporate Governance (ESG) viewpoint	The study demonstrates useful practices in policies and decision-making processes regarding contract timing and pricing with contractors, assigning the number of lamps required, and selecting appropriate lamp types
[29-39]	2015-2022	Demonstrate LED Failure Modes, its associated testing methods, LED standards and Reliability Criteria	1) LED system failures are categorized as catastrophic or parametric failures, attributable to various stress factors; 2) IEC standards describe test methods for LED modules, lamps, and luminaires but do not predict lifetime; 3) ANSI/IES LM-80 is used to measure and project the life of LED packages; 4) Lumen maintenance and light source consistency are two criteria for measuring LED reliability or life expectancy.

3. Results and Discussion

3.1. Lighting design strategies

3.1.1. Simulation tools and associated strategies

There are multiple metrics to guide lighting design by means of various simulation tools. The well-tabulated study showing popular simulation tools for artificial lighting simulation with associated parameters [7] indicates lighting simulation studies have grown considerably since 2010, primarily on office-scaled models. Within 74 reviewed articles, around 70% of them investigated multiple objective functions simultaneously instead of only focusing on illumination and a large majority focused on energy. In terms of popularity of simulation tools by 2018, the top three singly used simulation tools were MATLAB, EnergyPlus and DOE, which are relatively poor at user operation interfaces, while the top three were EnergyPlus/Radiance, EnergyPlus/MATLAB MATLAB/LABVIEW, MATLAB/Transient System Simulation (TRNSYS) for features enhancements. Even multi-purpose simulation tools occupied half the popularity in previous studies, but they were mainly geared toward a specific use (thermal, energy and lighting simulation) without information exchange within all modules of a simulation system, and individual case studies required multiple instantiation efforts. Along with the prosperous development in 3D modelling after 2018, there has been an increase in the use of 3D modeling software, specifically Rhino and its-based plugins, for lighting design research [8]–[11]. These plugins are based on the RADIANCE engine and have similar features that enhance the understanding of how the built environment interacts with the surrounding climate and enable the optimization of lighting design for energy efficiency, environmental sustainability, and human factors such as visual comfort, circadian rhythm, and well-being. This growing trend is driven by advances in technology and a growing awareness of the importance of lighting in promoting health, productivity, and safety under complex lighting scenarios in the last five years. Micolier et al., addressed these weaknesses and proposed an agent-based model that simulates occupants' behaviour in a building and their indoor comfort together with lighting purposes [4]. This agent-based model is suitable for early-stage building studies post-Covid, since it includes both individual agents and social interaction. Chokwitthaya et al., have also published similar works. A computational framework was developed to improve the prediction accuracy of conventional building performance models. In the framework, an artificial neural network is employed to combine context-aware design, which uses specific data obtained from immersive virtual environments within conventional building performance models. For the additional purpose of better data collection, the framework also has the capability to rank the influence of factors impacting human-building interactions through a feature ranking technique [1]. A similar rationalization sequence is also supported in studies using simulation models for daylighting, artificial lighting, and mixed lighting. With the validation of practical measurements and the creation of a digital twin in the simulation tool, a general rationalization algorithm for redesigned lighting was developed [12].

From another aspect, Jalaei et al., provided a framework to automate the process sustainability assessment for proposed buildings. By integrating Building Information Model (BIM) and LEED certification system, it optimized the credits that a building could potentially earn at the conceptual stage. [13]. After 2020, there was widespread interest in deep networks as a technique for visual quality improvement. Shang et al., designed a synthetic-real interaction training strategy that synthesizes the low-light image pairs by treating the depth map as the illumination. In this way, it is possible to get the supervised labels for simulating the smoothed property of the illumination. This will avoid designing complex regularization losses, which may have minor effects [14].

3.1.2. Lighting metrics and application targets

Since 2003, EU countries had a common standard of EN 12464-1:2011 for lighting planning of workplaces indoors. After 10 years, a new European edition entered into force. The EN 12464-1:2021 principally aims to solve bad design and lighting issues that raised from minimum requirements and missing key details. The main changes are around 1) definition of several design areas with relevant design requirements; 2) addressing the idea of maintenance factor in the recommended illuminance values; 3) extra considerations of lighting control, energy and cost [15]. Meanwhile, the release of the technical specification, BIM properties for lighting– luminaires & sensing devices further helps in making informed decisions during the design, construction, and operation phases of a building project [16]. The main contributions of this technical specification are illustrated in Figure 3.

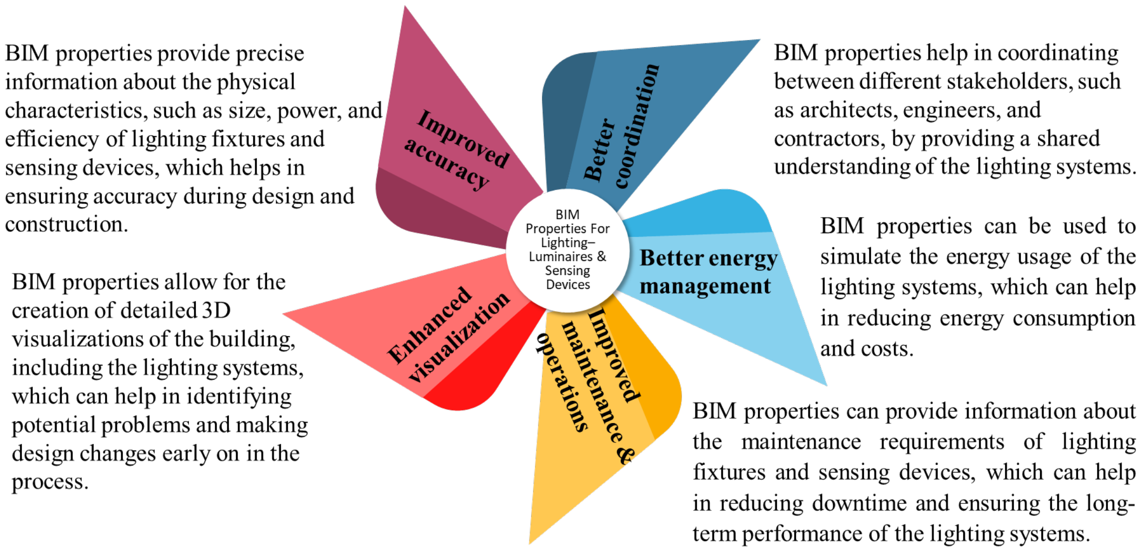

Figure 3 How can BIM model contributes to lighting design and management

The main changes in the latest two documents exactly match to the main research concerns. Both energy efficiency and visual comfort are two key goals around lighting design. In order to achieve the single goal of lighting energy savings, Seo and Yun sorted out three mechanisms: 1) improving efficiency with light source replacement; 2) adjusting illuminance level with lowering luminaire output; 3) reducing the surplus consumption in the absence of occupants with the help of different control system [17].

Lighting retrofits can substantially reduce the energy use of existing buildings in addition to HVAC. In order to achieve that goal, façades and roofs should incorporate active and passive strategies [12]. The parametric study provides a method for balancing energy control and natural lighting harvest.

Commonly studied natural lighting optimization strategies involve factors such as the orientation and form of buildings, the atrium element and the geometrics of openings and side lighting [18], [19]. Albatayneh et al., offered useful guidance regarding the optimum Window-Wall-Ratio (WWR) for key decision-makers when designing energy-efficient buildings in Jordan. The findings indicated that the typical WWR in Jordan that have efficient LEDs lighting installed could be lower than the highest WWR stipulated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards [20].

Instead of the classical approach based on static metrics—i.e., Daylight Factor, dynamic metrics provide a more accurate quantification of energy savings in electric lighting when compared to traditional daylight static concepts. By means of daylight dynamic metrics including continuous daylight autonomy, Acosta et al., assessed the energy efficiency of climate-smart lighting management with the impact of the proposed solutions on economic profitability. These variables are derived from more involved variables, such as weather conditions, occupancy hours or illuminance thresholds [21]. In addition, dynamic metrics satisfy the growing demand for human-centred design. Yilmaz investigated the impact of human factors on retail lighting design by means of an experimental subjective approach for sales areas. This approach established a connection between luminous environment perception, price perception and quality perception of displayed products [2]. Additionally, with the recent development of ergonomic simulation tools. Simulation tools can be further used in the field of ergonomics to simulate, evaluate, or rationalize physical loads, physical factors of the working environment, or risks at the workplace. Dupláková et al., described the creation of an ergonomic rationalization algorithm for lighting design in a working environment [22].

3.2. Lighting asset management

3.2.1. Lighting controls

From the latest updates in The EN 12464-1:2021[15], it strongly indicates that smart controls are the next step after implementing energy-efficient lighting sources. The Standard lists several implement purposes that an adjustable system ensures: 1) To maximize available daylight; 2) To consider occupancy of the space; 3) To cater for changes in visual tasks, occupant's preferences or needs. The most common smart control principles are occupancy control systems, time-scheduling-based control systems, and daylight-linked control systems [17]. Within 74 reviewed scientific papers [7], there were 41 types of control systems associated with lighting systems. Fuzzy logic and MAST were most prevalent, while conventional ON/OFF was just one instance. Using energy-saving comparisons of lighting energy savings, Ismail et al., pointed out the importance of control grouping for building managers, even with manual ON/OFF controls [23].

In recent years, smart control has gained a lot of popularity with some innovative examples: passive infrared (PIR) control [17], dynamic control based on dynamic metrics [24] [21], lighting based on the Internet of Things (IoT) [25] and lighting management control using virtual submetering (VSM)[26]. Even for the most traditional occupancy sensing, it is possible to add more intelligence to lighting control. For instance, self-learning capabilities, would boost functionality and future flexibility further by means of advanced building asset management. It is possible that the next level of lighting control would mean enhancing parameters based on data [6].

3.2.2. Lighting asset management

At individual-built asset level, lighting is a specific type of facility that has detailed and fixed functionalities. Presently, it is imperative to integrate artificial intelligence into conventional lighting management systems to keep pace with the continuous development of new immerging lighting functionalities, intelligence, and green economies. Based on the normal distribution function, Mirzaei et al., proposed an asset-management model addressing challenges for regulators, managers, and operators of public-lighting systems [5]. Yoon et al. proposed the smart building light management system connected with the internet of things (IoT) featured lighting devices and its realization of human-centric lighting (HCL) control. Based on the streaming information from the camera, dynamic information is predicted, such as daylights and occupancy, occupancy specific emotional features predictions. Then the advanced computer vision techniques transmit the human-centric features to the smart building light management system for the purpose of light illumination regulating of the objective human-specific lighting devices [3]. Meanwhile, lighting is an essential element of emergency process management in public areas. Lin et al., undertook a comprehensive evaluation of an intelligent lighting system within the whole process of emergency management in the subway to achieve a rapid and effective response [27]. It is expected that along with the latest lighting product developments, it will lead to novel applications in building asset management, such as Light Fidelity (LiFi, instead of WiFi), indoor positioning, light as a service or light leasing [6].

At the building cluster level, lighting is relatively energy intensive. Such services are normally managed by three main participants: the regulatory unit, lighting managers, and private contractors. For most municipalities, one of the major problems is the lack of information about the actual state of public lighting systems. This information would allow us to know its consumption, costs and performance, safety, compliance with standards and potential for improvement [28]. Leccisi et al., presented an example within the framework of the Public Energy Living Lab (PELL) initiative launched by ENEA. The proposed PELL platform includes two phases: 1) the IoT platform represents the static phase. It aims to collect all the structural information concerning the state of public lighting plants through a census sheet, to evaluate and diagnose their performances and functionalities; 2) Data collection represents the dynamic phase. It aims to collect all the electric measurements provided by utilities and gathered at electrical panel level and aggregated at point of delivery (POD) level [28]. In their view, it is a key step in the development of a new efficient and effective model for managing public lighting. This will help transform urban centers into smart cities. Similarity, Subbarao et al., highlighted the critical components of a model "Smart and Digital Green Educational Campus" through IoT technology [25]. In this area, Mirzaei and his research team worked on this topic from two perspectives. The first study was to study the impact of annual growth in public lighting on the failure rate of lighting lamps. It depicted that the failure rate of lighting lamps increases in undeveloped and developing regions where there is demand for extending the lighting system each year. And the failure rate increases with the expansion of the public lighting network, but the failure rate associated with the initial extension is constant [29]. Another study assessed lighting services from an Environmental, Social, and Corporate Governance (ESG) viewpoint. The described case study of the public-lighting system demonstrated useful practices in policies and decision-making processes regarding contract timing and pricing with contractors, assigning the number of lamps required, and selecting appropriate lamp types [5]. At a building cluster level, it would be better to contribute to the discussion of pertinent topics such as specific lighting asset management protocols, facility capacities for upgrading lighting systems, city residents' preferences, and social welfare guarantees, etc.

3.2.3. Lighting lifetime evaluation

Nowadays, LED lamps have been widely used in the public lighting system with the benefits of energy efficiency and lower failure rate, when compared to the traditional fluorescent luminaires, high intensity discharge lamps, high-pressure mercury (HPM) or the high-pressure sodium (HPS) lamps [29]. Even so, LED systems still have a relatively high risk of failure associated with several subsystems and elements [30]. According to the literature, the failure of a LED lighting system can broadly be categorized as catastrophic type or parametric type. These failure modes are attributable to thermal, electrical, mechanical, environmental, chemical, and radiation stress factors [31]. There are two typical criteria for measuring LED lighting reliability or life expectancy, lumen maintenance and light source consistency through 3 common test methods [32].

As far as LED standards are concerned, there are a number of international standards that serve as the foundation for the definition and/or testing of LED product life. Globally, IEC standards mainly describe test methods for LED modules, lamps, and luminaires but without the intention of lifetime prediction. [33]–[35]. Currently, the Illuminating Engineering Society publishes both Technical Memorandums and Lighting Measurement and Testing (LM). ANSI/IES LM-80 [36] is the most recent version of the original standard used by the industry to measure and project the life of LED packages. The associated measuring method follows ANSI/IES TM-21-21[31]. In addition to LED packages, arrays, and modules, the LED system should comply with ANSI/IES LM-84-20+E1[38] which builds on the LM-80 document for measuring luminous flux maintenance of LED systems. While for public spaces such as retail, library and museum, there is a special requirement for color shift evaluation. The relevant standard is ANSI/IES TM-35-19+E1[39].

4. Conclusion

This article explores the key inferences from the reviewed 39 articles and standards within the aspects of lighting design strategies and lighting asset management (illustrated in both Figure 4 and Table 1). Such an international outlook is expected to be helpful in describing some of its key development lines which have influenced the lighting practices for Swedish public libraries.

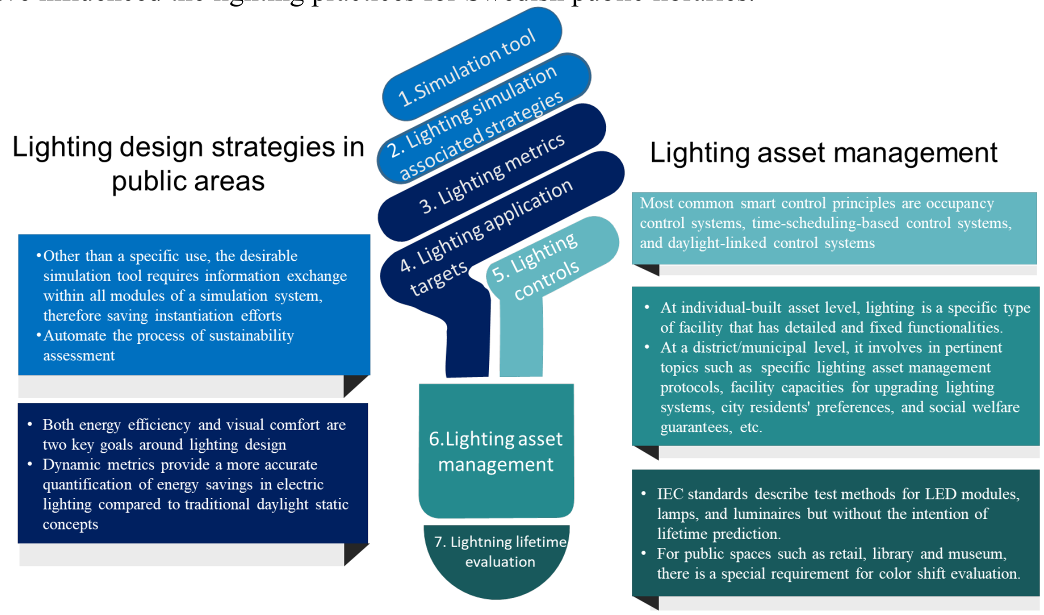

Figure 4 Summary of this review

Within this review, there are possible limitations from 1) insufficient studies caused by page restriction; 2) bias towards lighting asset management in the public areas due to the nature of the funded project's research objectives; 3) broad scope of the two interested research questions. However, it clearly identified the following future research tendencies.

1) Designing with high-precision simulation tools has become a prevalent trend in digital assisted lighting design. Although along with the prosperous development in 3D modelling after 2018, there has been an increase in the use of 3D modelling software, for lighting design research [8]–[11]. Here still requires a more dynamic bilateral information exchange between the physical asset and the virtual asset to provide detailed environment and boundary parameter inputs.

2) The main distinguishing parts for the peculiarity of the public-built environment/public areas, like public library lie in lighting asset management within 5 key aspects, as Inventory Management, Maintenance and Repairs, Energy Management, Asset Tracking and Reporting and Safety and Security. For public-lighting managers, energy bills and lighting product replacement are two common real challenges [5], [29]. It is imperative for conventional lighting management systems to keep pace with the continuous development of integrated lighting functionalities, intelligence control and green economies. This direction, which would be the future research trends, smart sensors enable automated

collection of environmental data, allowing for accurate monitoring and fine control. The two studied areas indicate that we have met the digitalization prerequisite to convert the conventional lighting from components and hardware driven to demands driven implementation.

3) Last but not least, it is worth preparing for the upcoming demographic shift that has challenges from a growing and ageing population, longer working time caused by later retirement age and urbanization in public-built environment/public areas. These all raise up higher lighting demands for visual comfort, biological and emotional performance. Within the digitalized new paradigms, the value of lighting should move from turning of/off mode into a wider spectrum in answering challenges of globalization (regulation and interface standards), and climate change (energy efficient and circular economy).

Acknowledgments

The authors would like to acknowledege that this project receives funding from the Swedish Energy Agency and Formas (Project number: P2022-00277).

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