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A context-driven reliability framework for lighting systems in public libraries under extreme and varying environmental conditions

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Abstract

In public buildings located in geographies with extreme and highly variable environmental conditions, such as Sweden, managing lighting systems reliably presents unique challenges. These arise not only from technical concerns like lifespan and energy use, but also from the need to ensure human well-being under seasonal extremes of natural light availability. This paper proposes a novel, context-driven framework for asset diagnostics and performance monitoring using two metrics: critical integrative levels—which classify lighting zones based on user activity, exposure time, and age group—and mean time of exposure, a newly introduced variable that quantifies user interaction with light in space and time. Three case studies across Swedish public libraries (from Luleå to southern Sweden) were used to validate the approach. The results show that integrating human-centric parameters into lighting diagnostics enables more responsive, context-aware threshold setting, compared to traditional functionality-based criteria (e.g. luminous flux percentage). Practical implications include earlier anomaly detection, prioritization of maintenance, and the ability to tailor lighting reliability metrics to real user needs, particularly under non-stationary environmental conditions. The proposed model provides a scalable structure for use in smart public infrastructure, aligning with Industry 5.0 principles. Future research will focus on extending the framework to automated digital twin environments, as well as exploring generalization across sectors such as healthcare, education, and transportation hubs.

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1. Introduction

Lighting systems in public buildings are increasingly viewed as critical socio-technical infrastructure, especially in regions where environmental variability affects both system performance and occupant well-being. In geographies such as Sweden, characterized by seasonally extreme daylight conditions—from prolonged winter darkness to near-continuous summer sunlight—managing lighting systems reliably poses unique challenges. These environmental shifts introduce non-stationary operational conditions, which complicate both traditional performance expectations and emerging demands for human-centric, health-supportive lighting.

In recent years, the concept of human-centric lighting—more broadly known as integrative lighting—has gained traction as an innovation frontier. Human-centric lighting extends beyond visual comfort to incorporate non-visual effects on human physiology, mood, cognition, and circadian regulation [1–3]. Global initiatives, such as the global lighting association's roadmap toward human-centric lighting by 2040 [1], have accelerated interest in adaptive lighting technologies capable of dynamically supporting user well-being across diverse spatial and environmental contexts.

Despite these advances in design, post-installation asset management remains rooted in conventional approaches that prioritize static performance indicators: energy use, lifespan, and basic visual compliance. These approaches often overlook variability introduced by user demographics, activity patterns, spatial zoning, and environmental conditions—especially in high-latitude settings. This gap limits the ability of public institutions to effectively monitor, diagnose, and optimize lighting assets in ways that align with both reliability goals and human-centric values.

Traditionally, reliability assessment in lighting systems has been based on predefined degradation thresholds that reflect changes in physical performance—for instance, a decline to 70%–80% of the original luminous flux. However, such thresholds often fail to consider user-centric operational realities, especially in dynamic environments like public libraries where user profiles, tasks, and lighting needs vary significantly across time and space.

In line with the transition toward Industry 5.0 and human-centric reliability engineering, this study introduces an alternative framing: diagnostic thresholds informed not solely by physical degradation, but by functional acceptability and user well-being. This represents a paradigm shift in how diagnostics and prognostics are defined for intelligent infrastructure—not merely based on when a system is 'out of spec' in engineering terms, but when it no longer meets the contextual needs of its users.

In the context of this study, a lighting system is considered reliable when it delivers an acceptable level of visual and non-visual performance for the intended users, within a specific spatial and temporal context. A system is degraded when its performance, though still operational, no longer meets user-based requirements defined by zone type, user age, and duration of exposure. A system is unreliable when it consistently fails to fulfil these functional expectations, even if it remains technically within manufacturer specifications (e.g. maintaining 80% luminous flux).

The proposed critical integrative levels (CILs) and mean time of exposure (MTOE) metrics operationalize this new framing by embedding user exposure, demographics, and environmental variability into the reliability model. As such, this approach expands the scope of diagnostics and monitoring to include both technological degradation and context-sensitive functional reliability.

The ongoing digital transformation in the building sector opens new opportunities to address these limitations. Emerging concepts such as digital twins, predictive maintenance, and adaptive diagnostics offer the potential to move from reactive to context-aware, proactive asset management [4–7]. However, the lack of practical methodologies that integrate environmental context, user exposure, and evolving well-being standards into operational reliability models remains a challenge. For example, studies such as [4] demonstrate energy-efficient lighting management, but do not assess system degradation from the user's perspective. Others (e.g. [5, 7],) highlight the potential of digital twins, but lack explicit integration of user activity, demographic needs, or spatial zoning into asset health modelling. Furthermore, existing diagnostic thresholds are typically defined in static terms (e.g. illuminance $\geqslant$ 300 lx), without considering how exposure time, user age, and zone type affect lighting acceptability. This study addresses these gaps by introducing a human-centric, adaptive approach to reliability assessment using CILs and MTOE as context-driven diagnostic variables.

To address this, the present study proposes a novel, context-driven framework for reliability assessment and performance monitoring of lighting systems in public libraries—institutions that are transitioning from static repositories of knowledge to dynamic, multi-functional community hubs. The framework introduces two core concepts:

- CILs: a matrix-based classification of lighting environments based on user age, activity, and exposure time.
- MTOE: a newly defined metric quantifying the average duration of user interaction with lighting zones, informing adaptive thresholds and health status diagnostics.

Together, CIL and MTOE enable a scalable methodology for assessing system health, detecting anomalies, and prioritizing maintenance actions—all while maintaining alignment with human-centric performance goals. By integrating visual and non-visual lighting parameters, this approach supports the development of reliable, context-aware lighting systems under extreme and varying environmental conditions.

One case study across three Swedish public libraries—from Luleå (66° N) in the Arctic north to southern Sweden—serve as the empirical basis for testing and refining the proposed method. The studies demonstrate how contextual thresholds can be established and used to guide lighting management in buildings affected by both seasonal climatic extremes and diverse user profiles.

This paper contributes to the advancement of digitalized, human-centric reliability engineering, with implications for smart building management, public policy, and the sustainable transformation of indoor environments in both Nordic and global contexts. Following the introduction, the structure of this paper is arranged to explore and elucidate the intricacies of human-centric and integrative lighting asset management in public libraries, guided by the proposed CILs and the concept of MTOE. Section 2 lays the groundwork with an identification of key performance parameters and contexts of lighting in public libraries. Section 3 delves into the MTOE and CIL, highlighting their integration to refine management practices. Section 4 discusses the establishment of context-specific CIL thresholds, enriched with illustrative examples. Section 5 transitions to the practical application of the CIL framework through case studies, section 6 discusses the principal findings from our studies, focusing on the degradation of key lighting parameters, nuances of equivalent melanopic lux (EML), comparative measurements across different seasons and libraries, and the intricacies of energy efficiency. Section 7 provides the conclusion together with future work. This compact structure aims to offer a comprehensive yet concise exploration of innovative strategies for managing lighting assets in the public libraries, emphasizing human well-being and operational efficiency.

2. Background: lighting parameters and contexts in public libraries

Section 2 provides essential lighting parameters identified on its performance measurement to public libraries and describes the typical lighting contexts these institutions encounter. This sets the stage for a deeper understanding of the contents in sections 3 and 4.

2.1. Identification of key lighting parameters on its performance measurement

This section identifies key parameters that reflect the performance of lighting, which refer to: illuminance, glare, colour rendering, colour temperature, flicker, chromaticity, photobiological safety, EML, energy efficiency, life span, and other factors. More sub parameters are listed in table 1 (also briefly illustrated by figure 1 in [4]). These parameters provide a comprehensive view of a lighting system's performance and how well it meets the needs and preferences of users. Standards for acceptable levels of most of these parameters are set by organizations like the Illuminating Engineering Society (IES) and the International Electrotechnical Commission. An overview of those key lighting parameters on its performance measurement is presented:

- Illuminance is a fundamental lighting performance parameter that measures the amount of light incident on a surface. It is expressed in lux (lx), where one lux is equal to one lumen per square meter. This parameter is crucial as it directly relates to how well a task can be visually performed, and it influences comfort and productivity. Related indices to illuminance help in determining the effectiveness and suitability of a lighting system for a given space and task requirements. They are important for assessing visibility, ensuring comfort, and promoting energy efficiency.
- Glare is a significant lighting performance parameter which refers to the discomfort or impairment of vision a person can experience when parts of their visual field are much brighter than the level to which their eyes are adapted. Glare can be detrimental to both comfort and safety, especially in tasks that require precision and focus. Related indices to glare help in assessing and mitigating the negative impacts of glare in various lighting situations. They are important in maintaining visual comfort and ensuring that lighting systems are designed and installed in a way that minimizes glare.
- Colour rendering refers to how accurately a light source reveals the colour s of objects, people, and surroundings in comparison to a natural light source (usually sunlight). The quality of colour rendering can greatly impact the appearance of a space and the activities within it. Related indices to colour rendering help in choosing the appropriate light source for various applications where the appearance of colour is critical, such as retail, art galleries, healthcare facilities, and more.
- Colour temperature is a measure that describes the spectral characteristics of a white light source, particularly the 'warm' or 'cool' qualities of the light. The colour temperature of a light source is determined by comparing its hue with a theoretical, heated black-body radiator. The temperature at which the heated black-body radiator matches the hue of the light source is the light's colour temperature, measured in degrees Kelvin (K). Related indices to colour temperature help in choosing the appropriate light source for various applications where the colour temperature plays a significant role, such as mood setting, light satisfaction and aesthetic purposes in interior design, film, and photography, and many more.
- Flicker is a rapid change in brightness of a light source over time. It is often caused by fluctuations in the electrical power supply. High levels of flicker can cause discomfort, fatigue, and even seizures in individuals with photosensitive epilepsy. Even at levels that are undetectable to the human eye, flicker can cause headaches and visual impairment.

Table 1. Key lighting parameters on its performance measurement.

Category	Sub-category	Comments
Illuminance	Average illuminance	This refers to the average level of light distributed over a particular surface or area. It is generally used to ensure sufficient lighting for tasks carried out in that area.
	Maximum illuminance	This refers to the point of highest light level on a given surface. It is important to avoid excessive maximum illuminance that can cause glare and discomfort.
	Minimum illuminance	This refers to the point of lowest light level on a given surface. It is crucial to ensure the minimum illuminance is still sufficient for visual tasks to prevent strain and fatigue.
	Uniformity ratio of illuminance	This is the ratio of minimum to average or maximum illuminance. Uniformity is key to avoid sharp contrasts in lighting, which can cause visual discomfort and impair task performance.
	Maintained illuminance	This is the illuminance level that lighting installations are designed to provide over most of their operational life, considering factors such as depreciation of lamp output and room surface dirt depreciation.
Glare	Direct glare	This occurs when bright lights are directly in the field of view. It is usually caused by inadequately shielded light sources and can cause discomfort and reduced visual performance.
	Discomfort glare	This type of glare causes discomfort without necessarily impairing the clarity of a scene. It is often caused by high contrasts or extreme brightness levels within the field of view.
	Unified glare rating (UGR)	UGR is a numerical measure of the glare in a particular environment, considering factors such as the size, position, and luminance of light sources, as well as the viewing angle. Lower UGR values correspond to less glare.
	Glare rating (GR)	This is another numerical measure of glare, primarily used in outdoor lighting. Like UGR, lower GR values indicate less glare.
	Glare by reflection	This occurs when light sources are reflected off shiny or glossy surfaces, causing bright spots that can distract or impair vision.
	Veiling reflection	This is a type of glare caused by reflections that wash out the colour s and contrast in a scene, making it difficult to see details clearly.
Colour rendering	Colour rendering index (CRI)	The CRI is a quantitative measure of the ability of a light source to reveal the colour s of various objects faithfully compared to an ideal or natural light source. The index ranges from 0 to 100, with a CRI of 100 representing the maximum possible colour rendering quality.
	General colour rendering index (R_a)	This is the average of the first eight colour rendering indices (R1 through R8) in the CRI calculation, which represent common colour s such as light and medium skin tones, sky blue, foliage green, etc. Like CRI, it is a measure of how accurately a light source can render these colour s compared to natural light.
	Special Colour rendering Index (R_i)	This includes the colour rendering indices from R9 to R14, which represent saturated colour s such as red, yellow, blue, and green. These indices are important in situations where accurate colour rendering of these specific colour s is crucial.
	Fidelity Index (R_f)	The Fidelity Index is part of the IES TM-30 colour rendering system, which is an advanced method of evaluating colour rendition. Rf measures how closely the colour rendering of a light source match that of a reference illuminant, with values ranging from 0 to 100.
	Gamut index (R_g)	Also part of the IES TM-30 system, the Gamut Index measures the average level of colour saturation when illuminated by the test source compared to the reference illuminant.

(Continued.)

Table 1. (Continued.)

	Standard deviation of colour matching (SDCM)	The term 'MacAdam Ellipse' or 'MacAdam Step' originates from David Lewis MacAdam's 1942 research, which established that the human eye cannot detect colour differences within specific ellipses in chromaticity space. These ellipses measure colour deviation with a unit called the 'Standard Deviation of Colour Matching' (SDCM), also known as 'MacAdam SDCM.' One SDCM, or one MacAdam Step, represents the smallest noticeable deviation. A colour tolerance of 3 SDCM, for instance, indicates that colour variations are within three MacAdam ellipses, and such differences are typically imperceptible. This metric is crucial in lighting design and quality control, particularly for ensuring colour consistency across LED lighting, where colour output can vary significantly between units.
Colour Temperature	Correlated colour temperature (CCT)	CCT is a specification of the colour appearance of the light emitted by a lamp, relating its colour to the colour of light from a reference source when heated to a particular temperature, measured in degrees Kelvin (K). Lower CCTs (2000–3000 K) are described as 'warm' and have a reddish-yellowish appearance, while higher CCTs (5000–6500 K) are referred to as 'cool' and have a bluish-white appearance.
	DUV	This is a measure of the deviation of a white light source from the black-body line in the CIE 1960 colour space. A Duv of zero means the colour point falls on the black-body line, indicating that the light source has the purest white colour corresponding to its CCT. A positive Duv indicates a shift towards green, while a negative Duv indicates a shift towards magenta. The DUV value that is considered acceptable for human perception and application requirements can vary depending on the context and the specific standards applied. In general, for most indoor lighting applications where colour quality is important, such as in residential or office settings, a DUV value close to zero is preferred, typically within the range of -0.003 to $+0.003$.
Flicker	Flicker frequency	This is the rate at which the light output fluctuates. It is measured in Hertz (Hz). A higher frequency is generally less noticeable and thus less likely to cause discomfort or health issues.
	Flicker percentage	This measures the amount of fluctuation in light output, usually as a percentage of the total light output. Higher percentages generally mean the flicker is more noticeable.
	Flicker index	This is a more complex measure that considers both the amplitude and the waveform of the flicker. It ranges from 0 (no flicker) to 1 (maximum flicker).
	SVM	Stroboscopic visibility measure (SVM) measures the visibility of stroboscopic effects from temporal light modulation, which can occur when moving objects are illuminated by a flickering light source.
Chromaticity	Chromaticity coordinates	In a chromaticity diagram, the colour of the light is represented by a point defined by two (in CIE 1931 or CIE 1960 space) or three (in CIE 1976 space) chromaticity coordinates. The most used are the x and y coordinates in the CIE 1931 space. For instance, the chromaticity coordinates of the D65 illuminant (representing average daylight) are (0.3127, 0.3290) in the CIE 1931 space.
	Chromaticity diagram	This is a plot of the chromaticity coordinates. In the CIE 1931 chromaticity diagram, the outer edge represents the spectrum of visible light, the colour s of the rainbow from red to violet, and the interior points represent the nonspectral colour s which can be formed by mixing light of different wavelengths.

(Continued.)

Table 1. (Continued.)

Category	Sub-category	Comments
	Chromaticity tolerances	This refers to the allowable deviation from a specified set of chromaticity coordinates, representing the colour consistency of a batch of lamps or luminaire. It is usually represented by a small area on the chromaticity diagram, within which the chromaticity coordinates of all samples must fall. The MacAdam ellipse is a common way to define chromaticity tolerances, where a one-step MacAdam ellipse is barely noticeable to the human eye.
Photobiological safety	Ultraviolet, UV	Photobiological safety refers to the measures and standards in place to protect humans from the potential harmful effects of exposure to optical radiation, including ultraviolet (UV) light, visible light, and infrared radiation. It primarily concerns mitigating risks associated with UV exposure, which can range from minor to severe health issues.
Circadian rhythm	Equivalent melanopic lux (EML)	Equivalent Melanopic Lux (EML) is a vital metric for evaluating light's impact on human health, particularly regarding circadian rhythms and cognitive functions. It centres on how light affects the eye's melanopsin-containing cells, which influence sleep, mood, and alertness.
Energy Efficiency	Luminous efficacy	This is a measure of how well a light source produces visible light. It is calculated by dividing the luminous flux (in lumens, lm) by the power consumed to produce that light (in watts, W). The higher the luminous efficacy, the more efficient the light source is at converting electricity into visible light.
	Lighting power density (LPD)	LPD is a measure of the power used by a lighting system per unit area of the space lit by the system. It is often measured in watts per square foot (W ft^{-2}) or watts per square meter (W m^{-2}). Lower LPDs mean that the lighting system is more energy efficient.
	Luminous efficiency	This is the ratio of the total luminous flux to the total radiant flux (total light output divided by total energy output). It is a measure of how efficiently a light source converts radiant energy into visible light.
	Energy star rating	In some regions, lighting products can receive an Energy Star rating if they meet certain criteria for energy efficiency. The Energy Star program is run by the U.S. Environmental Protection Agency and the U.S. Department of Energy.
Lifespan	Rated life	This is the estimated lifespan of a light source, provided by the manufacturer, based on standardized testing procedures. It represents the median operational life expectancy. For example, a typical incandescent light bulb may have a rated life of 1000 h.
	L70 and L50 Life	These are measures of how long it takes for a light source to degrade to a certain percentage of its original light output. L70 life is the estimated hours of operation until the light output degrades to 70% of its initial level. Similarly, L50 life is the time until the light output degrades to 50%. These are often used for LED light sources, which do not typically 'burn out' like other light sources, but gradually decrease in brightness over time.
	Survival rate	This is the percentage of a batch of lamps that continue to operate after a certain number of hours. For example, if 90 out of 100 lamps are still working after 1000 h, the survival rate is 90%.
	Maintenance factor	This factor considers the reduction in light output over time (lamp lumen depreciation), as well as other factors such as lamp failures, luminaire surface depreciation, and room surface dirt depreciation.
Luminaire	Shielding angle of luminaire	This is the angle below horizontal at which the lamp or light source in the luminaire is not directly visible, providing a measure of the luminaire's ability to control glare.
	Ingress protection (IP) rating	This is a rating system that defines the ability of a luminaire to prevent the ingress of dust and water. It is given as 'IP' followed by two digits, the first digit indicating the level of protection against solid objects and the second digit indicating the level of protection against liquids.

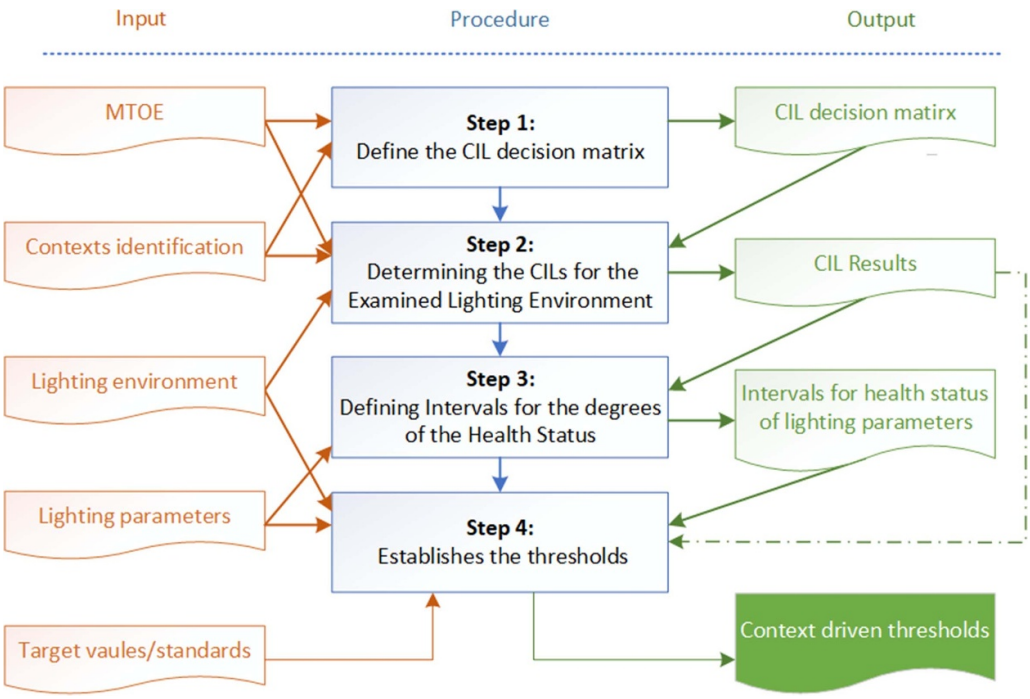


Figure 1. Input, output, and main steps in the procedure of setting context driven thresholds.

Related indices to flicker help in evaluating and minimizing the flicker in a lighting system, thereby ensuring visual comfort, and minimizing potential health risks.

- Chromaticity describes the specific colour of a light, independent of its luminance. It is usually represented in a two-dimensional chromaticity diagram, where each point corresponds to a specific colour. Related indices to chromaticity help in choosing the appropriate light source for various applications where the exact colour of the light is important, such as film and photography, retail, museums, and galleries, and more.
- Photobiological Safety refers to the potential risk of photochemical damage to the eye caused by electromagnetic radiation from light sources. The primary wavelengths of interest are the visible blue region between 400 nm and 500 nm. While modern LED light sources emit negligible amount of UV (ultraviolet) or IR (infrared radiation), the small size combined with substantial blue emission causes a high blue light hazard. The evaluation and classification are described in EN 62471 [8] and is required for luminaires installed in workplaces within EU through EU directive [9].
- EML is a crucial metric for assessing the impact of light on human health, focusing on its influence on circadian rhythms, sleep, and cognitive functions [10, 11]. It reflects the interaction of light with the eye's photoreceptors, particularly the melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs), which play a vital role in regulating emotions, alertness, and body temperature. Disruptions in ipRGC function due to inappropriate artificial lighting can result in sleep and mood disorders, among other health issues.
- Energy efficiency in lighting refers to the amount of light produced per unit of energy consumed. It is a crucial parameter in the design and operation of lighting systems, as improving energy efficiency can significantly reduce energy costs and environmental impacts. Related indices to energy efficiency help to evaluate and compare the energy efficiency of different lighting systems and to design lighting systems that minimize energy consumption and costs.
- The lifespan of a lighting source refers to the duration of its operation until it reaches a point where it can no longer perform its function adequately. It is a crucial factor when considering the cost, maintenance, and environmental impact of lighting systems. Related indices to lifespan help in planning the maintenance and replacement schedule of a lighting system, as well as in calculating the total cost of ownership, which includes not only the initial cost of the light source but also the costs of energy and maintenance over its operational life.
- Other Factors related to Luminaire: A luminaire, also known as a light fixture, is a complete lighting unit that includes a light source or light sources along with the parts designed to distribute the light, to position and protect the light sources, and to connect the light sources to the power supply. These indices help in selecting the appropriate luminaire for a particular application, considering both the lighting requirements and the energy efficiency.

2.2. Lighting contexts encountered in public libraries and their impact

A context-driven approach in human-centric and integrative lighting asset management, particularly within public

libraries, is pivotal for addressing the unique spectrum of challenges, user needs, and specific conditions inherent in such settings [5]. This approach acknowledges that libraries are not monolithic; they are dynamic environments influenced by a variety of factors. These factors, as detailed in previous studies and encapsulated [5], fall into several distinct categories: (1) external environmental factors, which include the impact of natural light and weather conditions; (2) interior design factors, which pertain to the architectural layout and aesthetic considerations; (3) user factors, focusing on the demographic diversity and the varying needs of library patrons; (4) cost factors, concerning budgetary limitations and economic efficiency; and (5) regulation factors, which involve compliance with legal and safety standards.

The human-centric and integrative approach to lighting asset management should acknowledge and cater to the varied needs of these demographic segments. For example, lighting requirements often differ across age groups. In sections of the library such as the magazine and newspaper area, which older adults commonly use, lighting with higher illuminance levels proves more suitable. Similarly, distinct activities necessitate unique lighting conditions. Reading, for instance, demands concentrated, brighter illumination, whereas social gatherings may be enhanced by softer, more diffuse lighting. Additionally, considering the library as a workplace for librarians introduces further lighting considerations. Task-specific lighting must be implemented in areas like the circulation desk and office spaces to reduce eye strain and improve efficiency. Ergonomic lighting design can also support librarians' health and productivity, highlighting the need for a multifaceted approach to lighting that considers the diverse roles a library plays for patrons and staff alike. For libraries situated in high-latitude areas of Sweden (above 55° N), the need for artificial lighting varies significantly with the seasons, attributable to the abundance of daylight in summer and prolonged darkness in winter. Consequently, this necessitates the adoption of diverse operational strategies to accommodate these seasonal variations in lighting requirements.

Understanding and recognizing these contexts is not merely beneficial but foundational to the process of lighting asset management in libraries. By thoroughly grasping the specific situations, settings, or environments, stakeholders can devise and implement a management approach that is not only tailored but also responsive to these diverse influences. This ensures that lighting solutions are not only technically viable but also human-centric, enhancing the user experience by meeting the specific needs dictated by these varied contexts.

In the preliminary framework of lighting asset management, the context-driven approach can offer essential guidance for establishing practical thresholds for the key performance indicators of lighting assets during the 'Study' stages [5]. This approach is crucial for addressing the issue that current thresholds, as identified in preliminary investigations, are determined solely based on standard recommendations. By incorporating a context-driven approach, we can ensure that lighting management strategies are more aligned with the actual needs and conditions of library environments, thereby enhancing the effectiveness and relevance of lighting solutions.

In essence, a context-driven approach enables the creation of lighting environments that are adaptable, efficient, and conducive to the multifaceted functions of modern public libraries, thereby underscoring its importance in the realm of library management. Additionally, our study adopts a dynamic approach to setting context-driven thresholds, which are not established as fixed, singular values but rather as a flexible matrix. This matrix is designed to adapt and meet the evolving requirements of human-centric and integrative lighting asset management. For more detailed information, please refer to section 3.

3. Novel thresholds: MTOE and the multidimensional CILs

Section 3 delves into the essence of human-centric and integrative lighting asset management, which prioritizes human well-being at the core of its decision-making process. This section introduces the novel concept of MTOE and present a novel, context-driven CILs approach for the effective management of lighting assets in public libraries. This includes an overview of assumptions and illustrative examples. The emphasis is placed on how the integration of these concepts can enhance management practices, ensuring that lighting solutions are not only efficient but also aligned with the specific needs and well-being of library users.

3.1. MTOE and CILs

MTOE is a concept designed to quantify the duration of human exposure to specified lighting conditions within a particular environment. It measures the average time individuals spend under these lighting conditions, reflecting the cumulative impact of lighting on human well-being and comfort. MTOE is a critical indicator in evaluating the suitability and effectiveness of lighting environments, particularly in spaces (such as public library) where visual tasks are performed or where lighting significantly influences mood, productivity, and circadian rhythms. MTOE, measured in minutes, is posited to correlate directly with the significance of a given environment to human well-being; that is, a larger MTOE indicates a greater importance of the environment to users' well-being. By assessing MTOE, stakeholders can make informed decisions to optimize lighting designs and configurations, ensuring they meet human-centric needs and enhance the overall user experience.

CILs signify the importance of a lighting environment, with a higher CIL denoting greater significance to human well-being, encompassing both physiological and psychological aspects. CIL determination integrates MTOE with various contextual factors. In this research, the innovative concept of CIL is depicted through a matrix that considers the user's age and MTOE within a public library setting. This study establishes several assumptions to elucidate the novel concept of CIL:

Assumption 1: The criticality of an environment is categorized into a higher CIL if the MTOE is 15 min or more. Conversely, an MTOE of less than 15 min categorizes the environment into a lower CIL.

- Higher CIL examples include settings such as reading sofas/tables, learning tables, and counters.
- Lower CIL examples encompass areas like bookshelves, digital inquiry tables, and corridors.

Assumption 2: The well-being of users of varying ages is considered differently, affecting lighting requirements. Environments predominantly used by individuals younger than 12 years or older than 65 years are assigned a higher CIL, reflecting the heightened importance of lighting for these age groups.

3.2. Establishing thresholds via context-driven CILs

This section details a step-by-step methodology for establishing thresholds using the context-driven CIL approach. The procedure of establishing the thresholds for a single lighting parameter is shown in below figure. Note: The target value (T) corresponds to the specifications set by the lighting designer, which are confirmed prior to the installation of the lighting assets. Typically, target values are set to achieve higher levels of lighting performance, whereas standard values define the basic acceptable levels.

Step 1: define the CIL matrix—The CIL matrix is formulated based on MTOE and the identified contexts pertinent to the study. For this research, the context in focus is the age of the users. According to table 2, users under 12 years of age are categorized into Group A, those over 65 into Group C, and all other users into Group B. Following Assumption 1 from section 3.1, an MTOE of less than 5 min is classified as T1, more than 15 min as T3, and durations in between as T2. Within this framework, CIL-I denotes a higher priority level than CIL-II. Specifically, CIL-I is assigned to Group A—T3, indicating a high CIL for lighting environments predominantly used by users younger than 12 for periods longer than 15 min, such as a children's reading area.

Step 2: determining the CILs for the examined lighting environment—This step involves identifying the CILs across the entire lighting environment under study, which, in this case, is the public library. As illustrated in table 3, this process entails analysing the specific sub-environments of lighting assets within the library and their primary users, identifying the age groups of these users and their MTOE. Utilizing the outcomes from the previous step, the appropriate CILs for each sub-environment are then established based on these factors.

Step 3: defining intervals for the degrees of the health status using the CIL matrix—The health status of each lighting parameter (as discussed in section 2.1) can be classified into varying degrees based on the CIL matrix. These degrees, corresponding to different CILs, determine the interval or range for each health status. An illustrative example is provided in figure 2, where, for instance, the health status (HS) of illuminance is categorized into five degrees, from HS1 to HS5, with HS5 being the optimal status. In the table, a 0% indication means that the actual value meets the requirements of standard limits (S). Target (T) values determined by the designer, which are set to achieve higher levels of lighting performance. It is important to recognize that exceeding necessary lighting values can lead to resource inefficiency, therefore the optimal achievable status is HS4, not HS5, to prevent wasteful over-illumination. Detailed intervals for the health status of lighting parameters are discussed in section 4. For parameters where a higher level indicates superior performance, such as HS5 being better than HS4, HS5 is highlighted in dark blue.

Step 4 Establishes the thresholds based on contact driven CIL matrix for the examined lighting environment—Based on the health status intervals set up in Step 3 and the target values for key lighting parameters in specified lighting environment, establishes the thresholds for each status. Take illuminance as example (see figure 2), for environments classified under CIL-I, the health status range is set to HS5, with the parameter's target value falling within a range of [T, 150% * T). Conversely, for CIL-II environments, the range is narrowed to [T, 120% * T). Target (T) values are typically established during the design phase by the lighting designers; however, in the absence of specific design data, standard values are used as benchmarks. This differentiation underscores the higher priority of CIL-I over CIL-II, reflected through broader health status intervals. Figure 3 presents some examples of setting thresholds of $\bar{E}_{\mathrm{m}}$ in the public library based on the above CIL matrix in figure 2, in which we assume the Target Value (T) is about 20% higher than the Standard value (S).

Unlike conventional threshold schemes that define asset health solely based on absolute performance metrics (e.g. illuminance below 300 lx), the proposed thresholds incorporate contextual parameters—including user age, activity type, spatial zone, and MTOE. This enables the adaptive redefinition of diagnostic thresholds to reflect when a system becomes functionally inadequate for its intended human use, even if technically still 'operational.'

From a reliability perspective, this method introduces a multi-dimensional degradation model in which system 'failure' is understood as loss of user-aligned function, not merely physical wear-out. This supports early-stage diagnostics, more meaningful prognostics, and context-prioritized maintenance planning.

4. A guide on context driven thresholds for key lighting parameters

Following the approaches proposed in sections 3 and 4 provides the thresholds established in the project for recommended key lighting parameters for monitoring and diagnostics. The recommended parameters are selected from the identified key parameters in section 2 (table 1), which provides a guide on setting context driven thresholds considering the needs on human centric and integrative lighting, requirement

Table 2. Context driven CIL matrix: an example.

MTOE/ages	Younger than 12 (group A)	Between (12, 65) (group B)	Older than 65 (group C)
Less than 5 (T1)	CIL-II	CIL-II	CIL-II
Between [5–15] (T2)	CIL-I	CIL-II	CIL-I
Longer than 15 (T3)	CIL-I	CIL-I	CIL-I

Table 3. Identified CILs with specified lighting environments: some examples.

Objectives_application_main users	Age group	MTOE	CIL
Bookshelf_Display_Adult	Group A, B, C	T1	CIL-II
Bookshelf_Reserve_Adult	Group B, C	T2	CIL-I
Table_Book borrow_digital_Adult	Group B	T1	CIL-II
Table_Book return_ Adult	Group A, B, C	T1	CIL-II
Table Counter_multifunction_Staff	Group B	T3	CIL-I
Sofa_Reading/learning_Adult	Group C	T3	CIL-I
Sofa_Reading/learning_Children	Group A	T2	CIL-I
Table_Digital inquiry_Adult	Group B	T1	CIL-II
Table_Reading/learning_multifunction_Adult	Group B	T3	CIL-I
Table_Reading/learning_digital_Adult	Group B	T3	CIL-I
Table_Hobby_Children	Group A	T2	CIL-I
Table_Workshop_Adult	Group C	T3	CIL-I

Visualization by colours	Health status (HS) degree	CIL-I	CIL-II
	HS1	[0, 95%*S)	[0, 90%*S)
	HS2	[95%*S, S)	[90%*S, S)
	HS3	[S, T)	[S, T)
	HS4	[T, 150%*T]	[T, 120%T]
	HS5	(150%*T, +8)	(120%T, +8)

Figure 2. Intervals for health status of lighting parameters: an example of illuminance $\bar{E}_{\mathrm{m}}$.

Main Objectives_Users	CIL	Standards/ Target	Health Status				
			HS1	HS2	HS3	HS5	HS4
Bookshelf_Display_Adult	II	300/400	(0, 270)	[270, 300)	[300, 360)	[360, 480]	(480, +8)
Bookshelf_Reserve_Adult	I	300/400	(0, 285)	[285, 300)	[300, 360)	[360, 600]	(600, +8)

Figure 3. Thresholds of $\bar{E}_{\mathrm{m}}$: some examples with $S = 300$, $T = 400$.

of standards, as well as target value from the lighting designers. These parameters (listed in table 4) are recommended for lighting performance measurement in public libraries for the purpose of monitoring and diagnostics. Some of the applications will be illustrated with case studies in section 5.

4.1. A guide on thresholds of illuminance: $\bar{E}_m$ and U_0

Illumination parameters should be in proximity of Target Value (T) to ensure a balanced lighting design throughout the library. Higher levels indicated as HS4 in $\bar{E}_{\mathrm{m}}$ will lessen energy efficiency. Based on Standard SS-EN 12464-1 [12], table 3 and figure 2, a guide on context driven threshold of $\bar{E}_{\mathrm{m}}$ can be found in figure 4, in which we assume the target (T) value, where $T\ (\bar{E}_{\mathrm{m}}) = S\ (\bar{E}_{\mathrm{m}}) + 100$, as shown in the figure 5. For U_0, we assume that $T\ (U_0) = S\ (U_0) + 0.1$. A U_0 of 1, which eliminates all shadows, could create a very clinical and monotonous atmosphere if applied throughout an entire library. Currently, we are using higher ratios only in specific areas such as sofas or tables to enhance those spaces. It is important to clarify that we are not advocating for a uniformity ratio of 1 across the entire library, as this might not provide the best aesthetic or functional outcome.

4.2. A guide on thresholds of glare: UGR_L

Glare needs to be avoided to ensure a good working environment. A glare rating lower than standard is desired. Based on Standard SS-EN 12464-1 [12], the variables are between 10 (best) −30 (worst). A guide on context driven threshold of $\mathrm{UGR_L}$ can be found in figure 6.

Table 4. Recommended lighting parameters for monitoring and diagnostics.

Category	Sub-category	Symbol
Illuminance	Maintained average illuminance	$\bar{E}_{\mathrm{m}}$
	Uniformity ratio of illuminance	U_0
Glare	Unified Glare Rating	$\mathrm{UGR_L}$
Colour rendering	Colour rendering Index R_a	R_{a}
	Colour rendering Index R_9	R_9
	TM-30 fidelity index	R_{f}
	TM-30 gamut area	R_{g}
	MACADAM	SDCM
Colour temperature	Correlated colour temperature	CCT
	Delta ultraviolet	DUV
Flicker	Stroboscopic visibility measure	SVM
Circadian Rhythm	Equivalent melanopic lux	EML

Visualization by colours	Health status degree	CIL-I	CIL-II
	HS1	[0, 95%*S)	[0, 90%*S)
	HS2	[95%*S, S)	[90%*S, S)
	HS3	[S, T)	[S, T)
	HS4	[T, 150%*T]	[T, 120%T]
	HS5	(150%*T, +∞)	(120%T, +∞)

Objectives/thresholds	CIL	S/T	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult/Children	II	300/400	(0, 270)	[270, 300)	[300, 360)	[360, 480]	(480, +∞)
Bookshelf_Reserve_Adult/Children	I	300/400	(0, 285)	[285, 300)	[300, 360)	[360, 600]	(600, +∞)
Table_Book borrow_digital_Adult	II	500/600	(0, 450)	[450, 500)	[500, 600)	[600, 720]	(720, +∞)
Table_Book return_ Adult	II	500/600	(0, 450)	[450, 500)	[500, 600)	[600, 720]	(720, +∞)
Table Counter_multifunction_Staff	I	750/850	(0, 713)	[713, 750)	[750, 850)	[850, 1275]	(1275, +∞)
Sofa_ Reading/learning_Adult	I	750/850	(0, 713)	[713, 750)	[750, 850)	[850, 1275]	(1275, +∞)
Sofa_ Reading/learning_Children	I	500/600	(0, 475)	[475, 500)	[500, 600)	[600, 900]	(900, +∞)
Table_Digital inquiry_Adult	II	500/600	(0, 450)	[450, 500)	[500, 600)	[600, 720]	(720, +∞)
Table_Reading/learning_multifunction_Adult	I	750/850	(0, 713)	[713, 750)	[750, 850)	[850, 1275]	(1275, +∞)
Table_Reading/learning_digital_Adult	I	500/600	(0, 475)	[475, 500)	[500, 600)	[600, 900]	(900, +∞)
Table_ Hobby_Children	I	500/600	(0, 475)	[475, 500)	[500, 600)	[600, 900]	(900, +∞)
Table_ Workshop_Adult	I	750/850	(0, 713)	[713, 750)	[750, 850)	[850, 1275]	(1275, +∞)

Figure 4. Intervals and context driven thresholds of $\bar{E}_{\mathrm{m}}$ compared to standard (S) and target (T) value.

Visualization by colours	Health status degree	CIL-I	CIL-II
	HS1	[0, 95%*S)	[0, 90%*S)
	HS2	[95%*S, S)	[90%*S, S)
	HS3	[S, T)	[S, T)
	HS4	[T, 120%*T]	[T, 110%*T]
	HS5	(120%*T, 1)	(110%*T, 1)

Objectives/thresholds	CIL	S/T	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	0.4/0.5	(0, 0.36)	[0.36, 0.4)	[0.4, 0.5)	[0.5, 0.55]	(0.55, 1)
Bookshelf_Reserve_Adult	I	0.4/0.5	(0, 0.38)	[0.38, 0.4)	[0.4, 0.5)	[0.5, 0.6]	(0.6, 1)
Table_Book borrow_digital_Adult	II	0.6/0.7	(0, 0.54)	[0.54, 0.6)	[0.6, 0.7)	[0.7, 0.77]	(0.77, 1)
Table_Book return_ Adult	II	0.6/0.7	(0, 0.54)	[0.54, 0.6)	[0.6, 0.7)	[0.7, 0.77]	(0.77, 1)
Table Counter_multifunction_Staff	I	0.6/0.7	(0, 0.547)	[0.57, 0.6)	[0.6, 0.7)	[0.7, 0.84]	(0.84, 1)
Sofa_ Reading/learning_Adult	I	0.6/0.7	(0, 0.547)	[0.57, 0.6)	[0.6, 0.7)	[0.7, 0.84]	(0.84, 1)
Sofa_ Reading/learning_Children	I	0.6/0.7	(0, 0.547)	[0.57, 0.6)	[0.6, 0.7)	[0.7, 0.84]	(0.84, 1)
Table_Digital inquiry_Adult	II	0.6/0.7	(0, 0.54)	[0.54, 0.6)	[0.6, 0.7)	[0.7, 0.77]	(0.77, 1)
Table_Reading/learning_multifunction_Adult	I	0.6/0.7	(0, 0.547)	[0.57, 0.6)	[0.6, 0.7)	[0.7, 0.84]	(0.84, 1)
Table_Reading/learning_digital_Adult	I	0.6/0.7	(0, 0.547)	[0.57, 0.6)	[0.6, 0.7)	[0.7, 0.84]	(0.84, 1)
Table_ Hobby_Children	I	0.6/0.7	(0, 0.547)	[0.57, 0.6)	[0.6, 0.7)	[0.7, 0.84]	(0.84, 1)
Table_ Workshop_Adult	I	0.6/0.7	(0, 0.547)	[0.57, 0.6)	[0.6, 0.7)	[0.7, 0.84]	(0.84, 1)

Figure 5. Intervals and context driven thresholds of U_0 compared to standard (S) and target (T) value.

Visualization by colours	Health status degree	CIL-I	CIL-II
	HS1	[S+1.5, +∞)	[S+3, +∞)
	HS2	[S+1.2, S+1.5)	[S+1.5, S+3)
	HS3	[S, S+1.3)	[S, S+1.5)
	HS4	[S-3, S]	[S-2, S]
	HS5	(0, S-3)	(0, S-2)

Objectives/thresholds	CIL	S	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	19	(22, +∞)	[20.5, 22)	[19, 20.5)	[17, 19]	(0, 17)
Bookshelf_Reserve_Adult	I	19	(20.5, +∞)	[20.2, 20.5)	[19, 20.2)	[16, 19]	(0, 16)
Table_Book borrow_digital_Adult	II	22	(25, +∞)	[23.5, 25)	[22, 23.5)	[20, 22]	(0, 20)
Table_Book return_ Adult	II	22	(25, +∞)	[23.5, 25)	[22, 23.5)	[20, 22]	(0, 20)
Table Counter_multifunction_Staff	I	19	(20.5, +∞)	[20.2, 20.5)	[19, 20.2)	[16, 19]	(0, 16)
Sofa_ Reading/learning_Adult	I	19	(20.5, +∞)	[20.2, 20.5)	[19, 20.2)	[16, 19]	(0, 16)
Sofa_ Reading/learning_Children	I	19	(20.5, +∞)	[20.2, 20.5)	[19, 20.2)	[16, 19]	(0, 16)
Table_Digital inquiry_Adult	II	19	(22, +∞)	[20.5, 22)	[19, 20.5)	[17, 19]	(0, 17)
Table_Reading/learning_multifunction_Adult	I	19	(20.5, +∞)	[20.2, 20.5)	[19, 20.2)	[16, 19]	(0, 16)
Table_Reading/learning_digital_Adult	I	19	(20.5, +∞)	[20.2, 20.5)	[19, 20.2)	[16, 19]	(0, 16)
Table_ Hobby_Children	I	19	(20.5, +∞)	[20.2, 20.5)	[19, 20.2)	[16, 19]	(0, 16)
Table_ Workshop_Adult	I	19	(20.5, +∞)	[20.2, 20.5)	[19, 20.2)	[16, 19]	(0, 16)

Figure 6. Intervals and context driven thresholds of $\mathrm{UGR_L}$ compared to standard (S) value.

Visualization by colours	Health status degree	CIL-I	CIL-II
	HS1	[0, 95%*S)	[0, 90%*S)
	HS2	[95%*S, S)	[90%*S, S)
	HS3	[S, T)	[S, T)
	HS4	[T, 115%*T]	[T, 110%*T]
]	HS5	(115%*T, 100)	(110%*T, 100)

Objectives/thresholds	CIL	S/T	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	80/85	(0, 72)	[72, 80)	[80, 85)	[85, 93.5]	(93.5, 100)
Bookshelf_Reserve_Adult	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Table_Book borrow_digital_Adult	II	80/85	(0, 72)	[72, 80)	[80, 85)	[85, 93.5]	(93.5, 100)
Table_Book return_ Adult	II	80/85	(0, 72)	[72, 80)	[80, 85)	[85, 93.5]	(93.5, 100)
Table Counter_multifunction_Staff	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Sofa_ Reading/learning_Adult	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Sofa_ Reading/learning_Children	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Table_Digital inquiry_Adult	II	80/85	(0, 72)	[72, 80)	[80, 85)	[85, 93.5]	(93.5, 100)
Table_Reading/learning_multifunction_Adult	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Table_Reading/learning_digital_Adult	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Table_ Hobby_Children	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Table_ Workshop_Adult	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)

Figure 7. Intervals for health status of CRI R_a compared to target and standard SS-EN 12 464–1 ($T = S + 5$).

4.3. A guide on thresholds of colour rendering: R_a, R_9, R_f, R_g, SDCM

The higher colour rendering, the better environment in the library. Colour rendering above target remains positive. Based on Standard SS-EN 12464-1 [12] and/or target, the variables R_a, R_9, R_f, are between 1–100, R_g is between 1–150. A guide on context driven threshold of R_a, R_9, $R_\mathrm{f}, R_\mathrm{g}$, SDCM, can be found in figures 7–11.

4.4. A guide on thresholds of correlated colour temperature and delta ultraviolet

The colour appearance of a light source refers to the apparent colour (chromaticity) of the light emitted. It is quantified by its CCT. The choice of colour appearance of the light is a matter of psychology, aesthetics and what is preferred. Lighting sources need to stay in proximity to target to ensure a pleasant environment. The CCT is regulated by the lighting designer. While standard such as SS-EN 12464-1 [12] has only recommendations for special conditions (not for libraries). In this study, we make suggestions including:

- For general reading areas, the average CCT could be 3500 K. The reason is that a neutral to cool white colour temperature helps in maintaining alertness and reduces eye strain, which is beneficial for reading and writing.
- For children's sections, the average CCT could be 3300 K. The reason is that a warmer colour temperature creates a welcoming and stimulating environment for children, which can be more comfortable and less harsh for young eyes.
- For computer and learning table areas: the average CCT could be 4000 K. The reason is that cooler white light is preferable where tasks require concentration and detail (such as computer use and research), as it promotes alertness and efficiency.
- For relaxation zones (sofa, etc): the average CCT could be 3000 K. The reason is that warm white lighting can make

Visualization by colours	Health status degree	CIL-I	CIL-II
	HS1	[0, 50%*T)	[0, 40%*T)
	HS2	[50%*T, 65%*T)	[40%*T, 55%*T)
	HS3	[65%*T, 80%*T)	[55%*T, 70%*T)
	HS4	[80%*T, T)	[70%*T, T)
	HS5	[T, 100)	[T, 100)

Objectives/thresholds	CIL	T	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	60	[0, 24)	[24, 33)	[33, 42)	[42, 60)	[60, 100)
Bookshelf_Reserve_Adult	I	60	[0, 30)	[30, 39)	[39, 48)	[48, 60)	[60, 100)
Table_Book borrow_digital_Adult	II	60	[0, 24)	[24, 33)	[33, 42)	[42, 60)	[60, 100)
Table_Book return_ Adult	II	60	[0, 24)	[24, 33)	[33, 42)	[42, 60)	[60, 100)
Table Counter_multifunction_Staff	I	60	[0, 30)	[30, 39)	[39, 48)	[48, 60)	[60, 100)
Sofa_ Reading/learning_Adult	I	60	[0, 30)	[30, 39)	[39, 48)	[48, 60)	[60, 100)
Sofa_ Reading/learning_Children	I	60	[0, 30)	[30, 39)	[39, 48)	[48, 60)	[60, 100)
Table_Digital inquiry_Adult	II	60	[0, 24)	[24, 33)	[33, 42)	[42, 60)	[60, 100)
Table_Reading/learning_multifunction_Adult	I	60	[0, 30)	[30, 39)	[39, 48)	[48, 60)	[60, 100)
Table_Reading/learning_digital_Adult	I	60	[0, 30)	[30, 39)	[39, 48)	[48, 60)	[60, 100)
Table_ Hobby_Children	I	60	[0, 30)	[30, 39)	[39, 48)	[48, 60)	[60, 100)
Table_ Workshop_Adult	I	60	[0, 30)	[30, 39)	[39, 48)	[48, 60)	[60, 100)

Figure 8. Intervals for health status of CRI R_9 compared to target ($T = 60$).

Visualization by colours	Health status degree	CIL-I	CIL-II
	HS1	[0, 95%*S)	[0, 90%*S)
	HS2	[95%*S, S)	[90%*S, S)
	HS3	[S, T)	[S, T)
	HS4	[T, 115%*T]	[T, 110%*T]
	HS5	(115%*T, 100)	(110%*T, 100)

Objectives/thresholds	CIL	S/T	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	80/85	(0, 72)	[72, 80)	[80, 85)	[85, 93.5]	(93.5, 100)
Bookshelf_Reserve_Adult	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Table_Book borrow_digital_Adult	II	80/85	(0, 72)	[72, 80)	[80, 85)	[85, 93.5]	(93.5, 100)
Table_Book return_ Adult	II	80/85	(0, 72)	[72, 80)	[80, 85)	[85, 93.5]	(93.5, 100)
Table Counter_multifunction_Staff	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Sofa_ Reading/learning_Adult	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Sofa_ Reading/learning_Children	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Table_Digital inquiry_Adult	II	80/85	(0, 72)	[72, 80)	[80, 85)	[85, 93.5]	(93.5, 100)
Table_Reading/learning_multifunction_Adult	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Table_Reading/learning_digital_Adult	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Table_ Hobby_Children	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)
Table_ Workshop_Adult	I	80/85	(0, 76)	[76, 80)	[80, 85)	[85, 97.75]	(97.75, 100)

Figure 9. Intervals for health status of CRI R_f compared to target and standard SS-EN 12 464–1 ($T = S + 5$).

Visualization by colours	Health status degree	CIL-I	CIL-II
	HS1	[1, 85]; [110, 150)	[1, 80]; [115, 150)
	HS2	(85, 90]; [105, 110]	(80, 85]; [110, 115]
	HS3	(90, 95]; [103, 105]	(85, 95]; [103, 110]
	HS4	(95, 99]; [101, 103]	(95, 99]; [101, 103]
	HS5	(99, 101)	(99, 101)

Objectives/thresholds	CIL	T	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	0	[1, 80]; [115, 150)	(80, 85]; [110, 115]	(85, 95]; [103, 110]	(95, 99]; [101, 103]	(99, 101)
Bookshelf_Reserve_Adult	I	0	[1, 85]; [110, 150)	(85, 90]; [105, 110]	(90, 95]; [103, 105]		
Table_Book borrow_digital_Adult	II	0	[1, 80]; [115, 150)	(80, 85]; [110, 115]	(85, 95]; [103, 110]		
Table_Book return_ Adult	II	0	[1, 80]; [115, 150)	(80, 85]; [110, 115]	(85, 95]; [103, 110]		
Table Counter_multifunction_Staff	I	0	[1, 85]; [110, 150)	(85, 90]; [105, 110]	(90, 95]; [103, 105]		
Sofa_ Reading/learning_Adult	I	0	[1, 85]; [110, 150)	(85, 90]; [105, 110]	(90, 95]; [103, 105]		
Sofa_ Reading/learning_Children	I	0	[1, 85]; [110, 150)	(85, 90]; [105, 110]	(90, 95]; [103, 105]		
Table_Digital inquiry_Adult	II	0	[1, 80]; [115, 150)	(80, 85]; [110, 115]	(85, 95]; [103, 110]		
Table_Reading/learning_multifunction_Adult	I	0	[1, 85]; [110, 150)	(85, 90]; [105, 110]	(90, 95]; [103, 105]		
Table_Reading/learning_digital_Adult	I	0	[1, 85]; [110, 150)	(85, 90]; [105, 110]	(90, 95]; [103, 105]		
Table_ Hobby_Children	I	0	[1, 85]; [110, 150)	(85, 90]; [105, 110]	(90, 95]; [103, 105]		
Table_ Workshop_Adult	I	0	[1, 85]; [110, 150)	(85, 90]; [105, 110]	(90, 95]; [103, 105]		

Figure 10. Intervals for health status of CRI R_g compared to target ($T = 95$).

Visualization by colours	Health status degree	CIL-I	CIL-II
	HS1	[5, +∞)	[6, +∞)
	HS2	[4, 5)	[5, 6)
	HS3	[3, 4)	[3, 5)
	HS4	[2, 3)	[2, 3)
	HS5	(1, 2)	(1, 2)

Objectives/thresholds	CIL	T	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	3	[6, +∞)	[5, 6)	[3, 5)	[2, 3]	(1, 2)
Bookshelf_Reserve_Adult	I	3	[5, +∞)	[4, 5)	[3, 4)	[2, 3]	(1, 2)
Table_Book borrow_digital_Adult	II	3	[6, +∞)	[5, 6)	[3, 5)	[2, 3]	(1, 2)
Table_Book return_ Adult	II	3	[6, +∞)	[5, 6)	[3, 5)	[2, 3]	(1, 2)
Table Counter_multifunction_Staff	I	3	[5, +∞)	[4, 5)	[3, 4)	[2, 3]	(1, 2)
Sofa_ Reading/learning_Adult	I	3	[5, +∞)	[4, 5)	[3, 4)	[2, 3]	(1, 2)
Sofa_ Reading/learning_Children	I	3	[5, +∞)	[4, 5)	[3, 4)	[2, 3]	(1, 2)
Table_Digital inquiry_Adult	II	3	[6, +∞)	[5, 6)	[3, 5)	[2, 3]	(1, 2)
Table_Reading/learning_multifunction_Adult	I	3	[5, +∞)	[4, 5)	[3, 4)	[2, 3]	(1, 2)
Table_Reading/learning_digital_Adult	I	3	[5, +∞)	[4, 5)	[3, 4)	[2, 3]	(1, 2)
Table_ Hobby_Children	I	3	[5, +∞)	[4, 5)	[3, 4)	[2, 3]	(1, 2)
Table_ Workshop_Adult	I	3	[5, +∞)	[4, 5)	[3, 4)	[2, 3]	(1, 2)

Figure 11. Intervals for health status of SDCM compared to target ($T = 3$).

those areas more inviting and relaxing, making it easier for people to unwind with a book.

Based on the above suggestions, a guide on context driven threshold of CCT can be found in figure 12.

The DUV value that is considered acceptable for human perception and application requirements can vary depending on the context and the specific standards applied. In general, for most indoor lighting applications where colour quality is important, such as in residential or office settings, a DUV value close to zero is preferred, typically within the range of -0.006 to $+0.006$ [13]. In this study, a guide on context driven threshold of CCT can be found in figure 13. This range ensures that the light colour is perceived as neutral white, without noticeable green or magenta tints that can be objectionable or cause discomfort over time.

4.5. A guide on thresholds of flicker parameter: SVM

SVM, the metric used to quantify the risk of stroboscopic effects that can be perceived by humans in a flickering light source. This is particularly relevant with the widespread use of LED lighting, which, if not properly controlled, can exhibit pronounced flicker. SVM values typically range from 0 to 1, with 0 indicating no visible stroboscopic effect and 1 indicating a highly noticeable effect. For library environments, where focused activities such as reading and computer work take place, it is important to minimize any potential for distraction or discomfort. Based on the Eco-design directive for regulation of maximum value [9], a guide on context driven threshold of CCT can be found in figure 14.

4.6. EML

The higher EML, the healthier contribution to the visual environment in the library. In certain settings, some positive compensations will differ from the dynamics in natural lighting environment. Based on WELL Standard [14], American National Standards RP-1-12 [15], British Standards Institution PD CEN/TR 16791:2017 [16], DIN/TS 5031-100:2021-11 [17], CIE S 026:2018 [18], A guide on context driven threshold of EML can be found in figure 15. Noted, this study takes recommended thresholds from WELL V2 in which EML is recommended to be >150 EML, while DIN standard generally recommends >250 EML.

5. Practical application of the CIL framework in public libraries

Building on the insights and the novel approach from previous sections, this section explores the practical implementation of the CIL framework through detailed case studies of three Swedish libraries, designated as G, S, and C. These studies, conducted with measurements taken in February for Library G, and in March and October 2023 for Libraries S and C respectively, utilize the GL SPECTIS 1.0 touch as the measurement tool (figure 16).

We have chosen nine key parameters to illustrate the application of the CIL framework, categorized into visual and non-visual/semi-visual groups. The visual parameters include Illuminance ($\bar{E}_{\mathrm{m}}$ in Lux), Colour Rendering Indices R_{a}, R_9, $R_{\mathrm{f}}, R_{\mathrm{g}}$, SDCM. The non-visual parameters assessed are CCT, DUV, SVM, and EML.

To contextualize our findings, we use the health status scale from HS1 to HS5, where HS1 denotes the worst condition and HS5 represents an extra good condition, as established in section 4. Main findings from the case studies include:

- Illuminance (Lux):
  - Approximately 50% of the measurements across the libraries fall into HS1 or HS2, indicating illuminance levels significantly below the standard and target values, depicted in red.
  - Instances of excessively high illuminance were observed, hinting at potential energy inefficiencies (highlighted in dark green, HS5), which are further discussed in section 6.

Visualization by colours	Health status degree	CIL-I	CIL-II
	HS1	[0, 60%*T)	[0, 50%*T)
	HS2	[60%*T, 90%*T)	[50%*T, 80%*T)
	HS3	[90%*T, 95%T)	[80%*T, 95%*T)
	HS4	[95%*T, 105%*T)	[95%*T, 110%*T)
	HS5	[105%*T, +∞)	[110%*T, +∞)

Objectives/thresholds	CIL	T	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	3500	(0, 1750)	[1750, 2800)	[2800, 3325)	[3325, 3850)	[3850, +∞)
Bookshelf_Reserve_Adult	I	3500	(0, 2100)	[2100, 3150)	[3150, 3325)	[3325, 3675)	[3675, +∞)
Table_Book borrow_digital_Adult	II	3500	(0, 1750)	[1750, 2800)	[2800, 3325)	[3325, 3850)	[3850, +∞)
Table_Book return_ Adult	II	3500	(0, 1750)	[1750, 2800)	[2800, 3325)	[3325, 3850)	[3850, +∞)
Table Counter_multifunction_Staff	I	4000	(0, 2400)	[2400, 3600)	[3600, 3800)	[3800, 4200)	[4200, +∞)
Sofa_ Reading/learning_Adult	I	3000	(0, 1800)	[1800, 2700)	[2700, 2850)	[2850, 3150)	[3150, +∞)
Sofa_ Reading/learning_Children	I	3000	(0, 1800)	[1800, 2700)	[2700, 2850)	[2850, 3150)	[3150, +∞)
Table_Digital inquiry_Adult	II	4000	(0, 2000)	[2000, 3200)	[3200, 3800)	[3800, 4400)	[5200, +∞)
Table_Reading/learning_multifunction_Adult	I	4000	(0, 2400)	[2400, 3600)	[3600, 3800)	[3800, 4200)	[4200, +∞)
Table_Reading/learning_digital_Adult	I	4000	(0, 2400)	[2400, 3600)	[3600, 3800)	[3800, 4200)	[4200, +∞)
Table_ Hobby_Children	I	3300	(0, 1980)	[1980, 2970)	[2970, 3135)	[3135, 3465)	[3465, +∞)
Table_ Workshop_Adult	I	4000	(0, 2400)	[2400, 3600)	[3600, 3800)	[3800, 4200)	[4200, +∞)

Figure 12. Intervals and context driven thresholds of CCT compared to target (T) value.

Visualization by colours	Health status degree	CIL-I	CIL-II
	HS1	(-∞, -0.005]; [0.005, +∞)	(-∞, -0.006]; [0.006, +∞)
	HS2	(-0.005, -0.004]; [0.004, 0.005]	(-0.006, -0.005]; [0.005, 0.006]
	HS3	(-0.004, -0.003]; [0.003, 0.004]	(-0.005, -0.003]; [0.003, 0.005]
	HS4	(-0.003, -0.001]; [0.001, 0.003]	(-0.003, -0.001]; [0.001, 0.003]
	HS5	(-0.001, 0.001)	(-0.001, 0.001)

Objectives/thresholds	CIL	T	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	0	(-∞, -0.006]; [0.006, +∞)	(-0.006, -0.005]; [0.005, 0.006]	(-0.005, -0.003]; [0.003, 0.005]	(-0.003, -0.001]; [0.001, 0.003]	(-0.001, 0.001)
Bookshelf_Reserve_Adult	I	0	(-∞, -0.005]; [0.005, +∞)	(-0.005, -0.004]; [0.004, 0.005]	(-0.004, -0.003]; [0.003, 0.004]		
Table_Book borrow_digital_Adult	II	0	(-∞, -0.006]; [0.006, +∞)	(-0.006, -0.005]; [0.005, 0.006]	(-0.005, -0.003]; [0.003, 0.005]		
Table_Book return_ Adult	II	0	(-∞, -0.006]; [0.006, +∞)	(-0.006, -0.005]; [0.005, 0.006]	(-0.005, -0.003]; [0.003, 0.005]		
Table Counter_multifunction_Staff	I	0	(-∞, -0.005]; [0.005, +∞)	(-0.005, -0.004]; [0.004, 0.005]	(-0.004, -0.003]; [0.003, 0.004]		
Sofa_ Reading/learning_Adult	I	0	(-∞, -0.005]; [0.005, +∞)	(-0.005, -0.004]; [0.004, 0.005]	(-0.004, -0.003]; [0.003, 0.004]		
Sofa_ Reading/learning_Children	I	0	(-∞, -0.005]; [0.005, +∞)	(-0.006, -0.005]; [0.005, 0.006]	(-0.005, -0.003]; [0.003, 0.005]		
Table_Digital inquiry_Adult	II	0	(-∞, -0.006]; [0.006, +∞)	(-0.006, -0.005]; [0.005, 0.006]	(-0.005, -0.003]; [0.003, 0.005]		
Table_Reading/learning_multifunction_Adult	I	0	(-∞, -0.005]; [0.005, +∞)	(-0.005, -0.004]; [0.004, 0.005]	(-0.004, -0.003]; [0.003, 0.004]		
Table_Reading/learning_digital_Adult	I	0	(-∞, -0.005]; [0.005, +∞)	(-0.005, -0.004]; [0.004, 0.005]	(-0.004, -0.003]; [0.003, 0.004]		
Table_ Hobby_Children	I	0	(-∞, -0.005]; [0.005, +∞)	(-0.005, -0.004]; [0.004, 0.005]	(-0.004, -0.003]; [0.003, 0.004]		
Table_ Workshop_Adult	I	0	(-∞, -0.005]; [0.005, +∞)	(-0.005, -0.004]; [0.004, 0.005]	(-0.004, -0.003]; [0.003, 0.004]		

Figure 13. Intervals and context driven thresholds of DUV compared to target (T) value.

Visualization by colours	Health Status (HS)	CIL-I	CIL-II
	1	[0.2, 1]	[0.25, 1]
	2	[0.15, 0.2)	[0.2, 0.25)
	3	[0.1, 0.15)	[0.1, 0.2)
	4	[T, 0.1)	[T, 0.1)
	5	(0, T)	(0, T)

Objectives/thresholds	CIL	T	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	0.05	[0.25, 1]	[0.2, 0.25)	[0.1, 0.2)	[0.05,0.1)	[0, 0.05)
Bookshelf_Reserve_Adult	I	0.05	[0.2, 1]	[0.15, 0.2)	[0.1, 0.15)	[0.05,0.1)	[0, 0.05)
Table_Book borrow_digital_Adult	II	0.05	[0.25, 1]	[0.2, 0.25)	[0.1, 0.2)	[0.05,0.1)	[0, 0.05)
Table_Book return_ Adult	II	0.05	[0.25, 1]	[0.2, 0.25)	[0.1, 0.2)	[0.05,0.1)	[0, 0.05)
Table Counter_multifunction_Staff	I	0.05	[0.2, 1]	[0.15, 0.2)	[0.1, 0.15)	[0.05,0.1)	[0, 0.05)
Sofa_ Reading/learning_Adult	I	0.05	[0.2, 1]	[0.15, 0.2)	[0.1, 0.15)	[0.05,0.1)	[0, 0.05)
Sofa_ Reading/learning_Children	I	0.05	[0.2, 1]	[0.15, 0.2)	[0.1, 0.15)	[0.05,0.1)	[0, 0.05)
Table_Digital inquiry_Adult	II	0.05	[0.25, 1]	[0.2, 0.25)	[0.1, 0.2)	[0.05,0.1)	[0, 0.05)
Table_Reading/learning_multifunction_Adult	I	0.05	[0.2, 1]	[0.15, 0.2)	[0.1, 0.15)	[0.05,0.1)	[0, 0.05)
Table_Reading/learning_digital_Adult	I	0.05	[0.2, 1]	[0.15, 0.2)	[0.1, 0.15)	[0.05,0.1)	[0, 0.05)
Table_ Hobby_Children	I	0.05	[0.2, 1]	[0.15, 0.2)	[0.1, 0.15)	[0.05,0.1)	[0, 0.05)
Table_ Workshop_Adult	I	0.05	[0.2, 1]	[0.15, 0.2)	[0.1, 0.15)	[0.05,0.1)	[0, 0.05)

Figure 14. Intervals and context driven thresholds of SVM compared to target (T) value.

Visualization by colours	Health Status (HS)	CIL-I	CIL-II
	1	<120 EML	<108 EML
	2	120-132 EML	108-120 EML
	3	132-150 EML	120-150 EML
	4	150-275 EML (Standard)	150-180 EML (Enhanced Daylight)
	5	>275 EML	>180 EML

Objectives/thresholds	CIL	S (EML)	HS1	HS2	HS3	HS4	HS5
Bookshelf_Display_Adult	II	150	(0, 108)	[108, 120)	[120, 150)	[150, 180]	(180, +∞)
Bookshelf_Reserve_Adult	I	150	(0, 120)	[120, 132)	[132, 150)	[150, 275]	(275, +∞)
Table_Book borrow_digital_Adult	II	150	(0, 108)	[108, 120)	[120, 150)	[150, 180]	(180, +∞)
Table_Book return_ Adult	II	150	(0, 108)	[108, 120)	[120, 150)	[150, 180]	(180, +∞)
Table Counter_multifunction_Staff	I	150	(0, 120)	[120, 132)	[132, 150)	[150, 275]	(275, +∞)
Sofa_ Reading/learning_Adult	I	150	(0, 120)	[120, 132)	[132, 150)	[150, 275]	(275, +∞)
Sofa_ Reading/learning_Children	I	150	(0, 120)	[120, 132)	[132, 150)	[150, 275]	(275, +∞)
Table_Digital inquiry_Adult	II	150	(0, 108)	[108, 120)	[120, 150)	[150, 180]	(180, +∞)
Table_Reading/learning_multifunction_Adult	I	150	(0, 120)	[120, 132)	[132, 150)	[150, 275]	(275, +∞)
Table_Reading/learning_digital_Adult	I	150	(0, 120)	[120, 132)	[132, 150)	[150, 275]	(275, +∞)
Table_ Hobby_Children	I	150	(0, 120)	[120, 132)	[132, 150)	[150, 275]	(275, +∞)
Table_ Workshop_Adult	I	150	(0, 120)	[120, 132)	[132, 150)	[150, 275]	(275, +∞)

Figure 15. Intervals and context driven thresholds of EML.



Figure 16. Measurement tool: GL SPECTIS 1.0 touch.

- Illuminance varies significantly with shelf height, with higher shelves typically experiencing better light levels (HS5), though medium and lower shelves often remain in poor conditions (HS1).

- Colour rendering:
  - Most data points scored well (HS4) or best (HS5) for colour rendering indices, except for notable issues with R9, particularly in Library C during conditions of low snow reflectance (October measurements), where R9 significantly worsened.
- CCT:
  - CCT values exhibited dependency on the measurement's vertical position, with about 50% rating as just acceptable or poor (HS2 or HS3), potentially due to inappropriate selection or degradation of light sources.
- Non-visual parameters:
  - DUV: the majority of DUV measurements are classified as good (HS4) or acceptable (HS3).
  - SVM: findings for SVM predominantly indicate good (HS4) or extra good conditions (HS5).
  - EML: EML calculations, heavily dependent on Lux and CCT, generally revealed less satisfactory statuses, warranting further discussion in section 6.

This section not only demonstrates the practical applications of the CIL framework but also highlights the complexities and challenges encountered in achieving optimal lighting conditions in library environments. The varying results across different parameters and conditions underscore the need for tailored lighting strategies that consider both visual comfort and energy efficiency.

6. Discussions

Building upon the case studies detailed in section 5, this section delves into a discussion of the principal findings from these studies. Our focus centres on the degradation of key lighting parameters, the nuances of EML, a simplified comparison on measurement results from different seasons and different libraries, and the intricacies of energy efficiency. Each of these elements plays a pivotal role in shaping the efficacy and sustainability of lighting asset management in public libraries.

6.1. Key lighting parameters degradation issues

Our analysis has revealed critical areas where lighting performance within public libraries needs urgent enhancement, specifically concerning Lux, R_9, CCT, and DUV see figures 17–21. The degradation of these parameters over time significantly impacts the overall effectiveness of lighting systems. Moreover, the calculations of EML are directly influenced by Lux and CCT values, suggesting that their degradation adversely affects EML outcomes.

Under the assumption that the initial design and installation being adequate, then the status of assessing those key lighting parameters shows that Lux, R_9, CCT, and DUV deteriorate with time. This natural progression underscores the necessity of incorporating these parameters into lifetime predictions and optimizing operational and maintenance strategies to extend the effective lifespan of lighting installations.

Current standards for defining the reliability of lighting sources, particularly LEDs, are predominantly cantered on the 'L70' benchmark [19]. This metric indicates when the luminous flux of LEDs declines to 70% of its initial output,

Objectives/thresholds	Comments			CIL	Visual						Non-Visual/semi-Visual		
	Shelf lighting	Daylight	Position		Lux	R_a	R_9	R_f	R_g	CCT	DUV	SVM	EML
Bookshelf_Display_Adult	Yes	No	High	II	1221	85	6	82	101	2929	0.0017	0	353
			Medium		344	86	14	86	98	2980	0.0008	0	105
			Low		233	86	17	87	98	3040	0.0015	0	72
Bookshelf_Display_Adult	No	Yes	High		240	95	61	95	98	4088	0.0026	0	98
			Medium		265	95	63	95	98	4450	0.0043	0	114
			Low		270	94	57	95	98	4150	0.0021	0	110
Bookshelf_Display_Adult	No	No	High		125	86	20	86	100	2396	-0.0042	0	34
			Medium		284	86	19	87	98	2755	-0.00224	0	84
			Low		320	85	16	86	97	2828	-0.0012	0	96
Table Counter_multifunction_Staff	/	/	/	I	370	84	14	86	96	3060	0.0005	0	116
Sofa_ Reading/learning_Children	/	No	/	I	700	86	13	86	99	3040	0.0008	0	215
Table_Reading/learning_multifunction_Adult	/	Yes	/	I	770	87	26	88	97	3360	-0.0003	0	263
Table_Reading/learning_digital_Adult	/	/	Table	I	470	84	14	86	96	3070	0.0003	0	147
	/	/	Screen		260	88	29	89	97	3250	0.0004	0	87
Table_ Hobby_Children	/	No	/	I	447	83	-1*	79	101	2838	0.0049	0	122

*: abnormal value(s)

Figure 17. Measurement and context driven assessment at library G_Feb2023.

Objectives/thresholds	Comments			CIL	Visual						Non-Visual/semi-Visual		
	Shelf lighting	Daylight	Position		Lux	R_a	R_9	R_f	R_g	CCT	DUV	SVM	EML
Bookshelf_Display_Adult	No	No	High	II	740	89	40	89	97	3010	-0.0019	1	241
			Medium		279	94	63	92	98	2911	-0.0016	0	92
			Low		268	94	63	92	98	2902	-0.0016	0	88
Bookshelf_Display_Adult	No	No	High		389	94	70	92	99	2675	-0.0031	4*	123
			Medium		185	95	71	92	99	2740	-0.0032	0	59
			Low		139	95	72	92	100	2734	-0.0033	0	44
Bookshelf_Display_Adult	No	Yes	High		1154	94	65	93	99	3411	0.0005	0	420
			Medium		215	95	73	95	98	3670	0.0022	0	83
			Low		215	95	70	95	98	3480	13*	0	80
Bookshelf_Display_Adult/Children	No	No	Medium		115	93	63	93	99	3071	0.0003	0	39
			Low		113	94	67	94	100	3112	0.0003	0	39
Table Counter_multifunction_Staff	No	No	/	I	300	94	64	93	100	3219	-0.0006	0	135
Sofa_ Reading/learning_Adult	No	Yes	/	I	1208	93	61	93	99	3250	0.0011	0	424
Table_Reading/learning_multifunction_Adult	No	No	Table	I	735	95	71	94	99	3602	0.0001	0	281
			Screen	I	650	94	69	94	99	3569	0.0006	0	241
Table_ Hobby_Children	No	Yes	/	I	1611	96	76	95	98	4056	0.0018	0	667

Figure 18. Measurement and context driven assessment at library S_Mar2023.

Objectives/thresholds	Comments			CIL	Visual						Non-Visual/semi-Visual		
	Shelf lighting	Daylight	Position		Lux	R_a	R_9	R_f	R_g	CCT	DUV	SVM	EML
Bookshelf_Display_Adult	No	No	High	II	570	90	44	89	97	2980	-0.0019	0	185
			Medium		300	93	63	91	98	2900	-0.0016	0	98
			Low		210	93	62	91	98	2900	-0.0016	0	69
Bookshelf_Display_Adult	No	No	High		250	94	72	92	99	2640	-0.0034	0	79
			Medium		122	95	72	92	100	2620	-0.0035	0	38
			Low		83	95	73	93	100	2600	-0.0037	0	28
Bookshelf_Display_Adult	No	Yes	High		1100	93	63	93	99	3300	0.0007	0	390
			Medium		300	93	62	92	99	3000	0.0004	0	100
			Low		230	93	62	92	99	3050	0.0004	0	104
Bookshelf_Display_Adult/Children	No	No	Medium		100	96	73	95	99	3250	-0.0004	0	36
			Low		74	94	65	93	100	2950	-0.0006	0	24
Table Counter_multifunction_Staff	No	No	/	I	340	93	60	92	99	3200	-0.0002	0	130
Sofa_ Reading/learning_Adult	No	Yes	/	I	1070	94	66	93	100	3300	-0.0002	0	379
Table_Reading/learning_multifunction_Adult	No	No	Table	I	160	93	62	93	99	2900	-0.0015	0	52
			Screen		225	96	71	95	99	3560	-0.0005	0	86
Table_ Hobby_Children	No	Yes	/	I	1150	94	68	94	98	3700	0.0009	0	443

Figure 19. Measurement and context driven assessment at library S_Oct2023.

traditionally used to estimate the lifespan of LED lighting. However, our findings advocate for a broader approach. Considering the degradation trends of not just Lux but also R_9, CCT and DUV is crucial as these factors are integral to maintaining optimal lighting conditions and enhancing the EML values.

Objectives/thresholds	Comments			CIL	Visual						Non-Visual/semi-Visual		
	Shelf lighting	Daylight	Position		Lux	R_a	R_9	R_f	R_g	CCT	DUV	SVM	EML
Bookshelf_Display_Adult	Yes	Yes	High	II	1390	92	37	89	100	3442	-0.0005	0.01	486
			Medium		820	95	58	94	100	3800	0.0004	0	321
			Low		800	97	69	96	100	4200	0.0007	0	358
Bookshelf_Display_Adult	No	Yes	High		730	97	98	98	101	5657	-0.0002	0	360
			Medium		335	95	69	95	101	3558	-0.0027	0	128
			Low		177	94	73	94	102	3431	-0.0043	0	67
Table Counter_multifunction_Staff	Yes	No	/	I	506	95	65	95	99	3914	0.0016	0	200
Table_Reading/learning_multifunction_Adult	No	No	Tabel	I	675	97	80	97	98	4758	0.0053	0	309
			Screen		380	98	90	98	99	4458	0.0021	0	170
Table_Reading/learning_digital_Adult	No	Yes	/	I	1100	97	76	95	101	4747	-0.0009	0	488
Table_ Hobby_Children	No	No	/	I	628	98	82	97	99	4258	0.0025	0	270
Table_ Workshop_Adult	Yes	Yes	/	I	770	91	33	88	101	3340	-0.0012	0	264

Figure 20. Measurement and context driven assessment at library C_Mar2023.

Objectives/thresholds	Comments			CIL	Visual						Non-Visual/semi-Visual		
	Shelf lighting	Daylight	Position		Lux	R_a	R_9	R_f	R_g	CCT	DUV	SVM	EML
Bookshelf_Display_Adult	Yes	Yes	High	II	970	85	3	80	102	2900	0.0008	0	276
			Medium		400	88	11	82	102	2770	-0.0005	0	115
			Low		310	89	11	85	102	2700	-0.0011	0	91
Bookshelf_Display_Adult	No	Yes	High		110	94	59	93	101	3400	-0.0017	0	40
			Medium		130	95	58	93	101	3500	-0.0013	0	48
			Low		80	95	58	93	101	3500	-0.0013	0	30
Table Counter_multifunction_Staff	Yes	No	/	I	570	87	23	85	101	3100	0.002	0	177
Table_Reading/learning_multifunction_Adult	No	No	Tabel	I	190	96	64	96	99	3900	0.0015	0	76
			Screen		100	94	54	93	101	3300	-00009	0	35
Table_Reading/learning_digital_Adult	No	Yes	/	I	750	96	68	95	100	4400	0.0016	0	320
Table_ Hobby_Children	No	No	/	I	/	/	/	/	/	/	/	/	/
Table_ Workshop_Adult	Yes	Yes	/	I	600	90	35	87	101	3400	0.0004	0	205

Figure 21. Measurement and context driven assessment at library C_Oct2023.

Additionally, the vertical position's impact on degradation is notable, with varying degrees of deterioration observed at different heights within the library spaces. This variation suggests that the commonly specified measurement height of 0.75 m [12] may be insufficient to capture the full scope of spatial lighting behaviour and degradation trends. Expanding the range of measurement heights could provide a more comprehensive understanding of lighting performance across different levels of a library's environment.

Overall, addressing these degradation issues not only involves revisiting maintenance schedules and operational practices but also calls for a re-evaluation of the metrics used to define lighting reliability and effectiveness. By broadening the scope of these metrics to include R_9, CCT and DUV alongside Lux, and considering the influence of vertical positioning, library lighting systems can be better maintained to serve their purpose over longer periods, ensuring both energy efficiency and high-quality illumination.

6.2. Circadian rhythms and EML

Daylight emerges as the most effective source of melanopic lux, as evidenced by its spectral composition and energy efficiency in comparison to artificial lighting sources. Our testing revealed that the presence of daylight yielded superior performance across various metrics in both visual and non-visual/semi-visual domains. Notably, daylight serves as a potent circadian stimulus, playing a crucial role in regulating circadian rhythms, influencing sleep–wake cycles, hormone production, and overall well-being.

While the integration of daylight into architectural design is commendable and reduces reliance on electrical lighting, the significant variability of sunlight throughout the year poses challenges. Figure 22 illustrates this variability, ranging from summer's midnight sun to winter's prolonged darkness. Such fluctuations present difficulties in fenestration placement, shading system control, and management of artificial lighting assets. Particularly during the highlighted orange timeframe of the year, the prolonged influence of natural lighting dynamics on human photoreceptors is evident. Exposure to natural daylight benefits cone cells, sensitive to bright light and colour perception, as well as ganglion cells, sensitive to blue light, thereby promoting alertness during daytime hours [20].

6.3. Comparison studies: from different seasons and different libraries

This section utilizes the median function to analyse metrics across three measured categories—visual parameters (Lux, R_9, and CCT), and non-visual parameters (DUV, SVM, and EML). Based on the results from figures 17–21, in this section, the health status (HS) of parameters is scored on a scale of 1–5 for each measurement, with each HS level corresponding to a specific score as detailed in figure 23. The median scores for all parameters are then compiled and presented in the final row of the table.

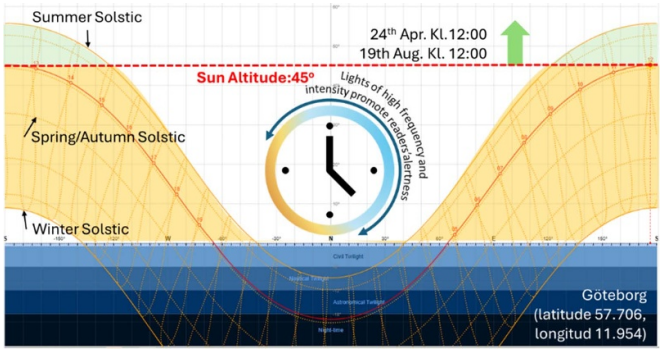


Figure 22. Cartesian sun-path diagram with recommended healthy CCT scale of Gothenburg, Sweden (Note: In our case study, library G is in the city of Gothenburg).

Objectives/thresholds	Position	Visual			Non-Visual/semi-Visual		
		Lux	R_9	CCT	DUV	SVM	EML
Bookshelf_Display_Adult	High	5	1	3	1	5	5
	Medium	3	1	3	5	5	1
	Low	1	1	3	4	5	1
Bookshelf_Display_Adult	High	1	5	5	4	5	1
	Medium	1	5	5	3	5	2
	Low	2	4	5	4	5	2
Bookshelf_Display_Adult	High	1	1	2	3	5	1
	Medium	2	1	2	4	5	1
	Low	3	1	3	4	5	1
Table Counter_multifunction_Staff	/	1	1	2	5	5	1
Sofa_ Reading/learning_Children	/	4	1	4	5	5	4
Table_Reading/learning_multifunction_Adult	/	3	1	2	5	5	4
Table_Reading/learning_digital_Adult	Table	1	1	2	5	5	2
	Screen	1	1	2	5	5	1
Table_ Hobby_Children	/	1	1	2	2	5	2
Median		1	1	3	4	5	1

Figure 23. From HS to scores.

Table 5. Scores of each library and average values.

Libraries/average	Lux	R_9	CCT	DUV	SVM	EML
Library G_Feb2023	1	1	3	4	5	1
Library S_Mar2023	1	5	3	4	5	2
Library S_Oct2023	1	5	3	5	5	1
Library C_Mar2023	4	5	5	4	5	4
Library C_Oct2023	1	3	3	4	5	1
Library_Average	1.6	3.8	3.4	4.2	5	1.8

Following the outlined approach, we have compiled scores for all five measurements in table 5. The average scores of these five measurements, representing a single data set or group, are displayed in the final row of the table.

As detailed in table 5, the results are depicted in figure 24, which presents data from Library S and Library C for the months of March and October, represented in blue and orange to signify spring and autumn, respectively. The average scores from these measurements are also highlighted in green within the figures.

The comparative analysis highlights distinct seasonal variations between the two libraries. While the differences in measurements between spring and autumn are minimal for Library S, they are more pronounced in Library C. This variance can largely be attributed to the architectural features of Library C, which includes extensive glass facades that significantly increase the influence of snow reflection during March. This finding underscores how human-centric and integrative lighting asset management strategies can be significantly affected by the physical characteristics of the building, particularly the presence of large glass areas (as also noted in [4]). This seasonal comparison not only reflects the direct impact of architectural elements on lighting conditions but also emphasizes the need for adaptive lighting strategies that can accommodate such variations effectively.

The comparative analysis highlights variations among the three libraries. Observing the green lines, which represent the average measurements, we note distinct differences: For Library S, the lighting performance is close to the average. In contrast, Library C performs above average, although it dips below the average in October. This comparison against

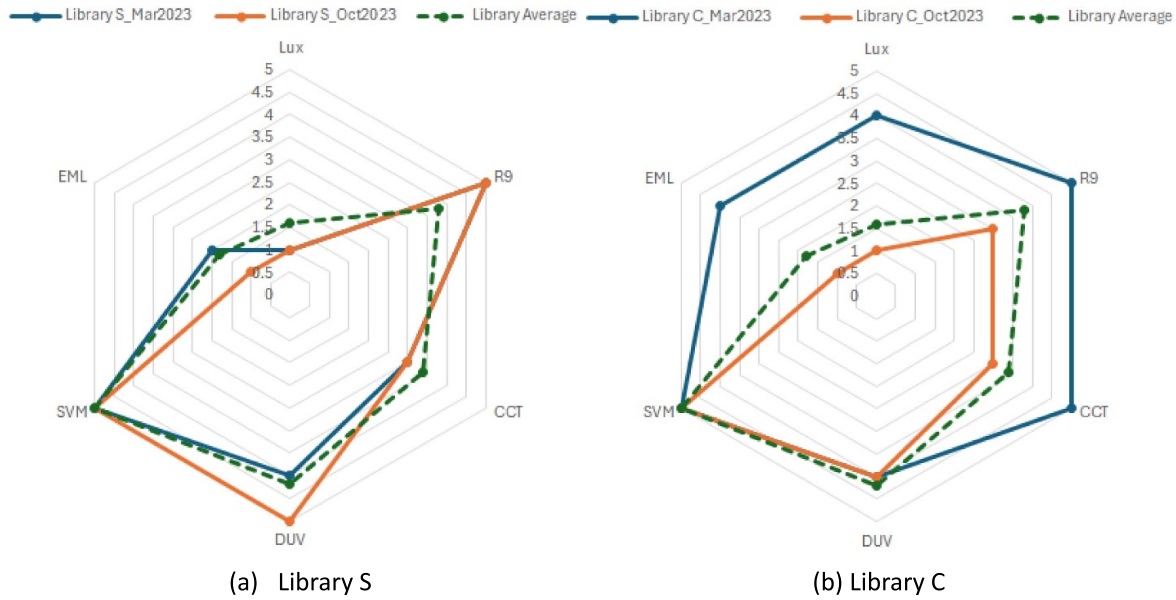


Figure 24. Radar diagram with median values from the measured visual, non-visual categories.

average levels underscores the disparities among libraries. Incorporating more measurements into the analysis provides deeper insights, enabling library asset managers to make more informed decisions tailored to specific needs at various levels.

6.4. Insights on energy efficiency

Typically, the energy efficiency of lighting sources is determined by dividing the declared useful luminous flux (in Lumens) by the declared on-mode power consumption (in Watts) and then multiplying by the applicable factor, resulting in ratings from A to G [9]. However, this method does not fully account for lighting performance or human needs in real indoor environments.

In terms of Lighting Asset Management, it is crucial to achieve an optimal balance between adequate daylighting and the mitigation of solar heat load to ensure an optimal indoor environment. For instance, during sunny winter periods, the use of shades to block excessive sunlight while still relying on artificial lighting can lead to inefficient energy use. Similarly, in sunny summer conditions, excessive solar gain can compromise thermal comfort, thereby increasing the need for cooling, which in turn raises energy consumption. These observations are consistent with the qualitative insights from our studies [4], which are further supported by quantitative measurements presented in section 5.

Swedish sustainable building certification standards, such as Miljöbyggnad [21], address these issues by incorporating the Solar Heat Load matrix, which quantifies solar heat transmitted through windows per square meter of floor area. This approach provides facility managers in libraries with a holistic view of fenestration strategies, shading control, and shading types.

Our case studies suggest that the energy efficiency of human-centric and integrated lighting assets should be evaluated based not only on energy consumption and individual lighting source' performance, but also on integrated lighting performance parameters in the real environment, such as Lux, R_9, CCT, DUV, SVM, and EML. Once the types of lighting sources in a library are established, their energy consumption can be considered constant. However, as the performance of these lighting parameters degrades over time, so too does the energy efficiency of the lighting assets. This degradation implies that energy efficiency diminishes over time and can be predicted based on the integrated degradation of these lighting parameters.

6.5. Reliability innovation

The proposed framework offers both theoretical and practical contributions to the emerging field of human-centric reliability engineering, particularly in the context of smart public infrastructure. From a reliability perspective, the CILs and MTOE enable a novel, user-context-driven degradation model. This shifts diagnostics away from static, hardware-based thresholds (e.g. 70% luminous flux) and toward functionality thresholds aligned with user needs, spatial conditions, and temporal patterns. Reliability degradation is thus reframed not only as physical failure, but as the loss of acceptable performance from the user's perspective, supporting more nuanced diagnostics and forecasting.

Practically, the framework allows lighting system operators to define adaptive, zone-specific diagnostic thresholds, which can be adjusted based on real-time user interaction data and environmental variability. This enhances early anomaly detection and enables prioritization of maintenance actions based on

how lighting degradation affects human well-being—not just technical performance. In this way, the approach aligns with Industry 5.0 principles by embedding human-centric intelligence into infrastructure diagnostics.

The framework is also designed for future integration with digital twin environments. CIL zoning can inform spatially resolved reliability maps, while MTOE can be used in predictive models to simulate system wear from a user-exposure perspective. This opens new possibilities for self-adaptive, intelligent lighting control that prioritizes zones critical to human health and productivity.

7. Conclusions and future research

This paper presented a novel framework for context-driven lighting asset management in public libraries, responding to the dual challenges of seasonally extreme environmental variability and the evolving demand for human-centric system performance. By introducing the concepts of CILs and MTOE, the study establishes a foundation for adaptive reliability assessment that integrates environmental, spatial, and user-centric factors into asset performance monitoring.

The proposed approach enables stakeholders to develop dynamic thresholds, enhance diagnostics and prognostics, and align lighting management practices with both technical reliability goals and human well-being outcomes. Through the case studies conducted across Sweden—from the Arctic city of Luleå to southern temperate zones—the methodology demonstrates its robustness in real-world contexts with climatic and demographic diversity.

Future work will extend this framework toward full integration with digital twin systems and automated maintenance platforms, enabling predictive analytics and cross-building benchmarking. Further research will also explore the scalability of CIL and MTOE across different public infrastructures (e.g. schools, hospitals, airports) and their alignment with emerging sustainability and accessibility standards.

This study contributes to the broader field of smart infrastructure reliability and offers a replicable model for enhancing lighting system safety, performance, and user experience in built environments exposed to non-stationary environmental conditions. The proposed methodology, while demonstrated in public libraries, is applicable to any public infrastructure where human experience, spatial context, and temporal usage patterns define system performance. Future research will apply this framework to hospitals, airports, and other smart buildings to evaluate its generalizability and scalability.

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