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Human-Centric Lighting Design: A Framework for Supporting Healthy Circadian Rhythm Grounded in Established Knowledge in Interior Spaces

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Abstract: Over the past 300 years, scientific observations have revealed the significant influence of circadian rhythms on various human functions, including sleep, digestion, and immune system regulation. Access to natural daylight is crucial for maintaining these rhythms, but modern lifestyles often limit its availability. Despite its importance, there is a lack of a comprehensive design framework to assist designers. This study proposes an architectural design framework based on the review of literature, lighting-related codes and standards, and available design and analysis tools that guides the creation of lighting systems supporting healthy circadian rhythms. The framework outlines key decision-making stages, incorporates relevant knowledge, and promotes the integration of dynamic lighting techniques into building design. The proposed framework was presented to a group of design professionals as a focus group and their feedback on the relevance and usability of the tool was obtained through a survey (n = 10). By empowering designers with practical tools and processes, this research bridges the gap between scientific understanding and design implementation, ensuring informed decisions that positively impact human health. This research contributes to the ongoing pursuit of creating lighting environments that support healthy circadian rhythms and promote human well-being.

Keywords: human-centric lighting; circadian rhythms; architectural design framework; healthy lighting; well-being

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1. Introduction

Around 300 years ago, French astronomer, Jean Jacques was the first person to scientifically study circadian rhythm. Since then, there has been extensive research on this topic, which has revealed various physiological processes, such as digestion, sleep, hormone release, blood pressure, and body temperature, are regulated by this internal clock [1–5]. It is important to note any alterations to this clock can affect a person's health and immunity [6].

The sun emits diffused rays in the sky that encompass all the necessary wavelengths to regulate the circadian rhythm of humans, animals, and plants [7]. Sufficient access to daylight can promote people's health and overall well-being. Nevertheless, with the modern lifestyle changes, this is becoming increasingly difficult to achieve [8]. Moreover, the human circadian rhythm is more affected by the short wavelengths of the visible light spectrum, and the widespread use of LED lighting may result in increased exposure to blue light at night, which could potentially have adverse effects on human health and well-being [7,9–11].

The non-visual response to light at night is influenced by several factors, including the intensity and duration of exposure to light, the color temperature of the light, as well as individual characteristics such as age, genetics, and behavior, which can impact sensitivity to light [12]. While the built environment cannot alter personal variables, there are several factors that affect human circadian rhythm in interior spaces, and many of them depend on the architectural lighting design. These factors are studied in the next part of the paper.

Several factors can serve as circadian biomarkers, including body temperature and various hormones. Nearly all hormones in the human body are released in a 24-h cycle that aligns with the circadian rhythm [13]. However, what distinguishes melatonin as the most advantageous hormone to be used as a circadian biomarker is its resilience to external influences [14]. While markers such as body temperature, heart rate, cortisol, and thyrotropin hormones can serve as circadian markers, they are susceptible to external factors such as stress and sleep [13]. In contrast, melatonin is not influenced by these factors, making it a more reliable circadian biomarker [15]. Therefore, melanopic equivalent daylight illuminance (Mel_EDI) serves as a metric facilitating the precise assessment of lighting's impact on the human circadian rhythm [11,16]. However, melanopic lux is deemed more convenient and practical for characterizing light sources. The simulation tools and scripts discussed later in this study are designed to measure melanopic lux, aligning with it being a recommended metric according to the WELL Building Standard [17]. As a result, for the scope of this paper, we choose to employ the melanopic lux metric.

Each architect and project follows a design process, though the nature of this process remains obscure despite attempts by structures and design frameworks to guide students and illustrate necessary steps. The complexity of the design process can be attributed to the various knowledge domains involved in architecture as a discipline, which comprise specific duties and pieces of knowledge that define it (Plowright, 2014) [18]. Plowright (2014) uses the analogy of food recipes to illustrate the process of architectural design. According to Plowright, the design process is comparable to a recipe, as it serves as a basis for refining and enhancing the skills of designers. Architecture involves the fusion of form-making with the influence of humans and the environment on it. Rather than producing works of art, architecture aims to create experiences that can be realized through the built environment. Plowright (2014) introduces design frameworks as an approach to design methodology. A concept-based framework, as he says, is one of the most challenging and widespread methods in architectural design. This technique involves developing a "big idea" that serves as a metaphorical representation of the various design elements that comprise the final structure.

This paper introduces a comprehensive framework that serves as the foundation for architectural design proposals focused on circadian lighting. It showcases the potential variability within its conceptual structures, emphasizing the flexibility of the framework to organize multiple approaches. The same underlying framework can adapt to diverse contexts, allowing for the infusion of varying priorities and generating distinct results. The primary goal is to develop a circadian rhythm design framework that promotes both health and effectiveness, offering designers valuable insights aligned with human physiological principles. The paper explores various elements influencing the human circadian rhythm in indoor environments, elucidating their impact on architectural and interior design. These elements are transformed into a versatile framework that architects and interior designers can employ to integrate circadian lighting design techniques into their projects. Additionally, the framework can serve as a foundational theme for studio projects in architecture education, facilitating student and educator engagement. The paper initially presents factors derived from the existing literature, introduces available tools, and concludes by presenting the final version of the framework.

2. Circadian Lighting in Architectural Design

Numerous sources provide definitions and explore the architectural design process. One prominent example is the American Institute of Architects (AIA) Council, which advocates for the adoption of Integrated Project Development (IPD) as a recommended approach [19]. Architectural design advancements can be accomplished through various approaches depending on the preferences of firms and business owners. In the past, the process used to be more linear, with each team member being responsible for a specific aspect and passing it on to the next group upon completion. In this conventional process, project success was detached from individual success. Conversely, the AIA strongly recommends replacing this approach with IPD. Unlike the sequential approach of traditional delivery, IPD promotes integrated teamwork from project inception. During the pre-design and pre-construction phases, the IPD team collectively establishes project goals and criteria. In the design and construction phases, collaboration is paramount, with the team working together to develop and refine design solutions, considering constructability and cost implications throughout. The implementation phase in IPD emphasizes ongoing collaboration, problem-solving, and adaptability. Even in the post-construction phase, the integrated team remains involved to address any issues and ensure the project aligns with the owner's expectations, marking a departure from the more segmented approach of traditional project delivery. This study uses the IPD method only to introduce different stages of the project and decisions that can be made for human-centric lighting design in each stage.

A framework has been developed based on the IPD stages and their definitions outlined in the AIA handbook. Figure 1 illustrates the typical project delivery process as defined by IPD, outlining the steps followed in each stage. However, the inclusion of the new concept of circadian lighting design introduces changes and additional steps that must be followed. The integration of this new concept necessitates site visits to assess lighting opportunities, along with training for team members and conducting research at every stage. The research evolves in the second stage to cover more specific concepts related to circadian lighting design (expert research), codes (evaluate codes and standards), and available technology (research technology).

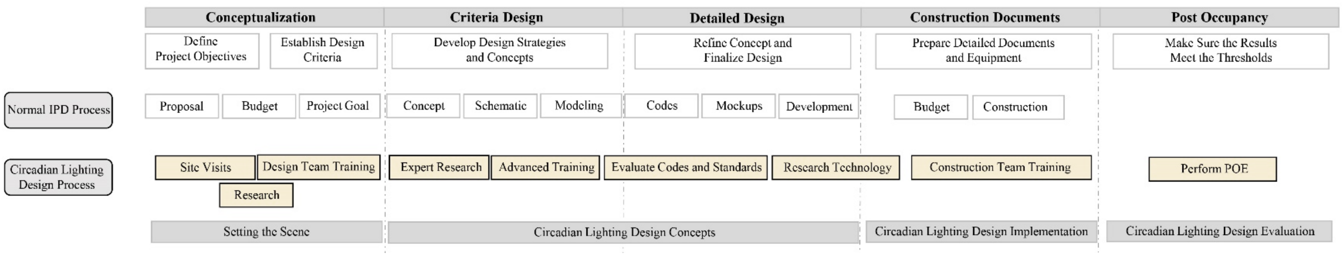

Figure 1. The first version of the framework based on the IPD and circadian lighting design as a new concept (source: author).

2.1. Setting the Project Goal and Site Studies

Setting the project goal early in the design process is of utmost importance [20]. It is crucial for every team member to have a clear understanding of the new concept that will be incorporated into the project. One of the important stages of every design process, especially in new construction, is the site analysis. This stage highlights the strengths and weak points of the site in terms of access to sunlight. This can affect the project form and location of important spaces to ensure enough access to daylight for all regularly occupied areas [21].

Figure 2 showcases several tools that designers can employ to conduct a comprehensive site analysis, ensuring successful outcomes. These tools encompass a range of approaches, including personal judgment, hand sketching, and photography, which are intrinsic to the designer's skillset. Furthermore, there are tools available for evaluating climate conditions and analyzing neighboring structures. These tools help in maximizing the daylight in early stages of design to ensure proper stimulation of circadian rhythm during the day. It is also crucial for the team to receive training on the physiological, psychological, and visual aspects of lighting design and its impact on health [22–24].

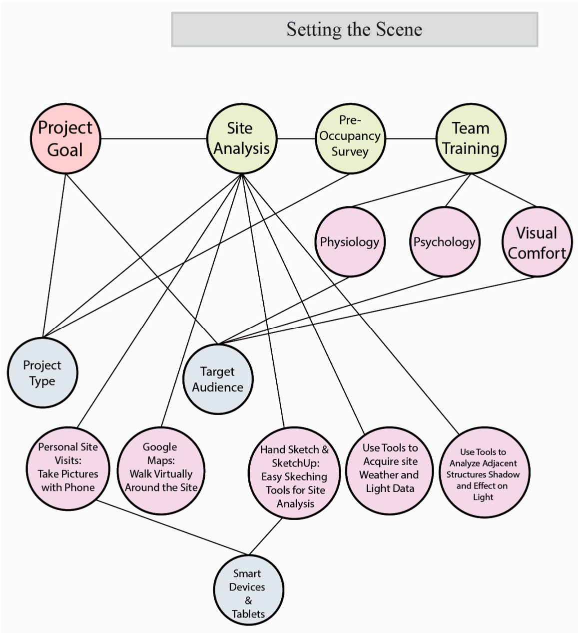

Figure 2. Setting the scene for early stages of design for circadian lighting (source: author).

2.2. The VITALS

The BIOS Lighting team, consisting of former NASA scientists, introduced six different factors to consider when designing spaces to support healthy circadian rhythm [25]. They called these factors VITALS. The VITALS criteria are presented as guidelines for human-centric lighting design. Here are the project VITALS:

1. Vertical—vertical light at the eye, vertical surfaces,
2. Intensity—light output,
3. Timing—consistent light cues each day,
4. Appearance—color quality and design,
5. Location—placement of lighting in a space,
6. Spectrum—the spectral make-up of a light source.

In circadian lighting design, the illumination of vertical surfaces at the observer's eye level (E_V) is more crucial than horizontal illuminance at the workplane (E_H). This is because vertical light has a more significant impact on the human circadian rhythm [26]. The intensity of the light is the second most crucial factor. Increased light intensity results in higher melanopic lux, which can disturb the circadian cycle at night and stimulate it in the morning [27]. The timing of lighting is another essential aspect to consider in designing lighting properties. It is crucial to replicate the natural patterns of light and dark in lighting design. At present, there exists a significant amount of research regarding the necessary daily dose of light to activate the daily circadian rhythm. The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute has developed a metric called Circadian Stimulus (CS), which proposes exposure to a CS value of $\geq$0.3 at the eye for a minimum of one hour in the early morning would be sufficient to trigger the circadian rhythm [28]. Additionally, the spectrum and color rendering index (CRI) should be appropriate to achieve a visually appealing design [29]. A lighting design that promotes good health is not valuable if it fails to provide visual comfort.

Light location pertains to the positioning of the light source. In natural settings, daylight typically originates from the horizon (the boundary between earth and sky), whereas below-horizon light sources such as fire were historically prevalent during evenings and nights. Light entering the eyes from below the horizon does not impact the human circadian rhythm [30]. Finally, the light spectrum is also a crucial factor to consider. Warm light sources produce a lower EML and have a lesser impact on the human circadian rhythm compared to cooler light sources [31–33].

2.3. Interior Design Elements

The main intent of this section is to emphasize the crucial role of design elements, such as interior paint color choices, seating direction, space allocation, and architectural factors like window size and location in influencing perceived spectrum and effective melanopic lux. The objective is to broaden the scope beyond lighting design, aiming for a comprehensive examination of all relevant factors.

It is crucial for architects to consider the impact of color on individuals of different ages and with varying disabilities. Research suggests lighting design influencing circadian rhythms can have distinct effects based on age, disabilities, and even conditions like autism and fragile X syndrome [34,35]. Consequently, understanding the target audience is crucial in the design process of a space. Moreover, interior paint color choice plays a role in human melanopic lux, with certain colors contradicting common beliefs about their calming effects. For instance, a study found cool colors like blue, often considered soothing, can lead to higher melanopic lux levels and suppress melatonin secretion at night [36].

Interior design elements significantly impact human circadian rhythm. Factors such as wall and furniture color, reflectance values, seating direction, and space allocation influence the perceived spectrum and effective melanopic lux [36,37]. Additionally, seating direction and space allocation affect the amount of vertical light received by the human eye and the amount of EML as a result [38]. There are many other architectural design elements that affect access to daylight in interior spaces, such as the number, size, and location of windows, room depth, shading devices and external obstructions, glazing properties, and so forth [39]. However, the lack of daylight in spaces should be supplemented with electric lighting. The information provided in the sections above populated the framework and is shown in Figure 3.

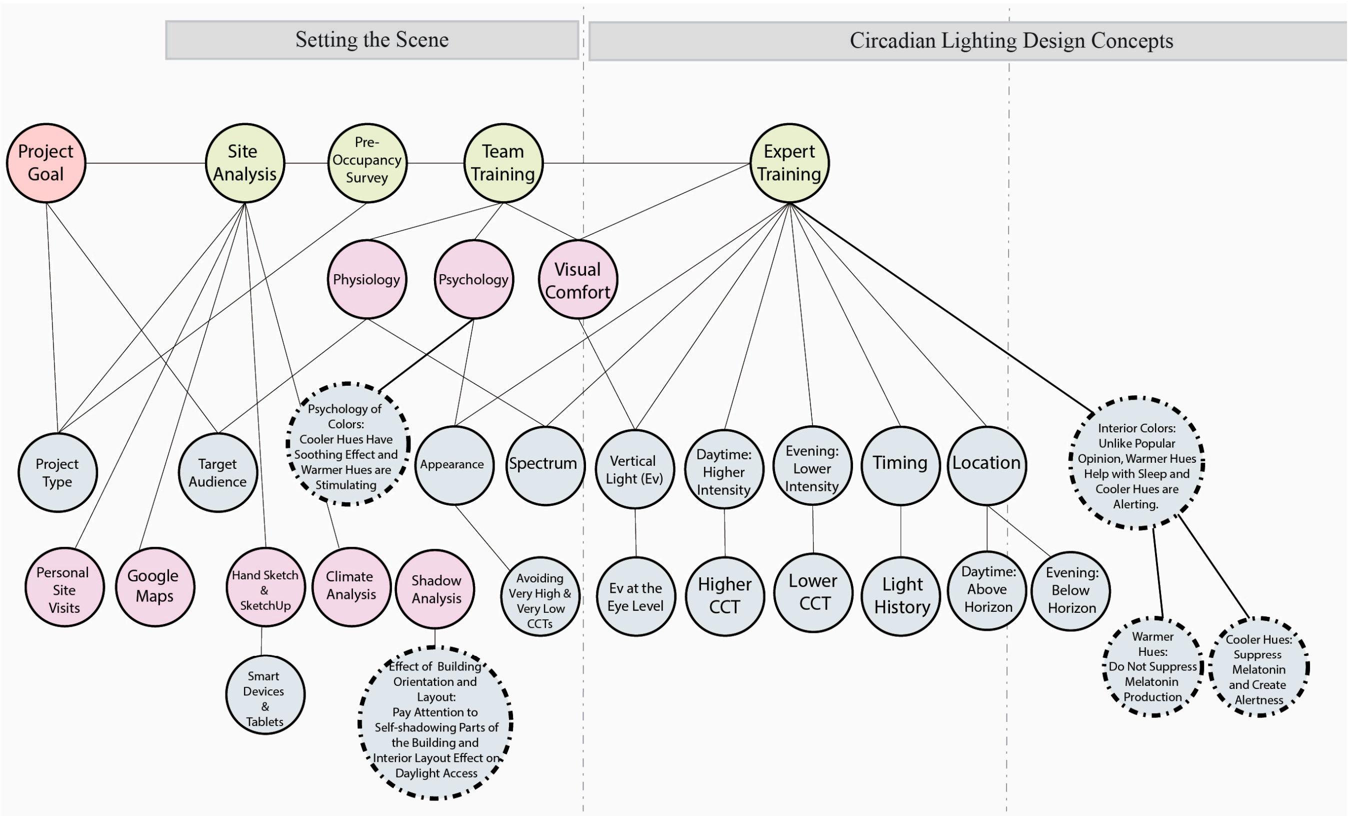

Figure 3. The new version of the framework based on the information from the sections above and the VITALS. The dotted circles show items added to the framework based on the Interior Design Elements section (source: author).

2.4. Tools in Circadian Lighting Design

New daylight and electric lighting analysis software is introduced daily. These software programs possess both similarities and differences and can conduct analyses at multiple levels. Each software package comes with its own set of advantages and disadvantages. However, due to the relative novelty of the circadian rhythm concept in architecture, there is a limited availability of software and design tools. Currently, the primary simulation software options are Solemma ALFA (2020 version, compatible with Rhino 6) [40] and LARK Spectral Lighting v1.0 [41]. While there are various methods for evaluating circadian lighting systems, based on the authors' research, only LARK and ALFA can operate using a 3D model and assess the lighting system following the design parameters. Results from ALFA and LARK can help evaluate the design for further improvements through an iterative process.

Alfa, a Rhino plugin, uses the radiance lighting engine to visualize environments and assess their impact on circadian lighting effects. It calculates non-image forming (NIF) photoreceptor-stimulating equivalent melanopic light (EML) considering sky conditions and electric light characteristics [40].

Similarly, LARK, a Grasshopper plugin, evaluates the effects of natural and artificial light on circadian rhythms, allowing designers to input specific details like materials and sky color. Developed in collaboration with ZGF Architects and the University of Washington, LARK is open-source for circadian light analysis [41]. Table 1 compares their capabilities, and Figure 4 illustrates their modeling and analysis procedures.

Table 1. LARK and ALFA input and output type comparison.

	LARK	**ALFA**
Sky	needs sky epw. file to generate spectral sky irradiance and global solar irradiance	data generated by user input of location and time
Sun	non-spectral sun	spectral sun
Sky condition	generated by global horizontal irradiance input	users can select from the software menu
Simulation type	9-channel	81-channel
Materials	spectral material text file to be inserted	spectral material library available
Results	point by point number	point by point and average numbers

Both LARK and ALFA serve as valuable tools for circadian lighting analysis, each with its unique features and considerations. As previously mentioned, ALFA distinguishes itself as a standalone tool with a user-friendly platform that facilitates ease of use without the need for extensive training. On the other hand, LARK demands a certain level of familiarity with Grasshopper. One notable advantage of LARK lies in its accessibility, being free and open-source, empowering users with greater flexibility and the ability to make modifications tailored to their needs. Both tools can help in modeling and analyzing daylight plus electric lighting to ensure proper systems are available to support human circadian rhythm.

Another tool for circadian lighting analysis is the Color and Illumination Calculator developed by the LRC at Rensselaer Polytechnic Institute (RPI). Although lacking 3D modeling capabilities, it serves as a valuable complement to the aforementioned tools. This online tool offers a user-friendly interface, allowing designers and professionals to calculate and analyze color and illumination parameters for various light sources and color combinations. Users can input specific data such as light source type, color temperature, and desired illuminance level, with the tool providing calculations for chromaticity coordinates, color rendering index (CRI), and other relevant parameters. Moreover, the tool allows visualization of the impact of different light sources and color combinations on objects and spaces in terms of color and illumination effects [42].

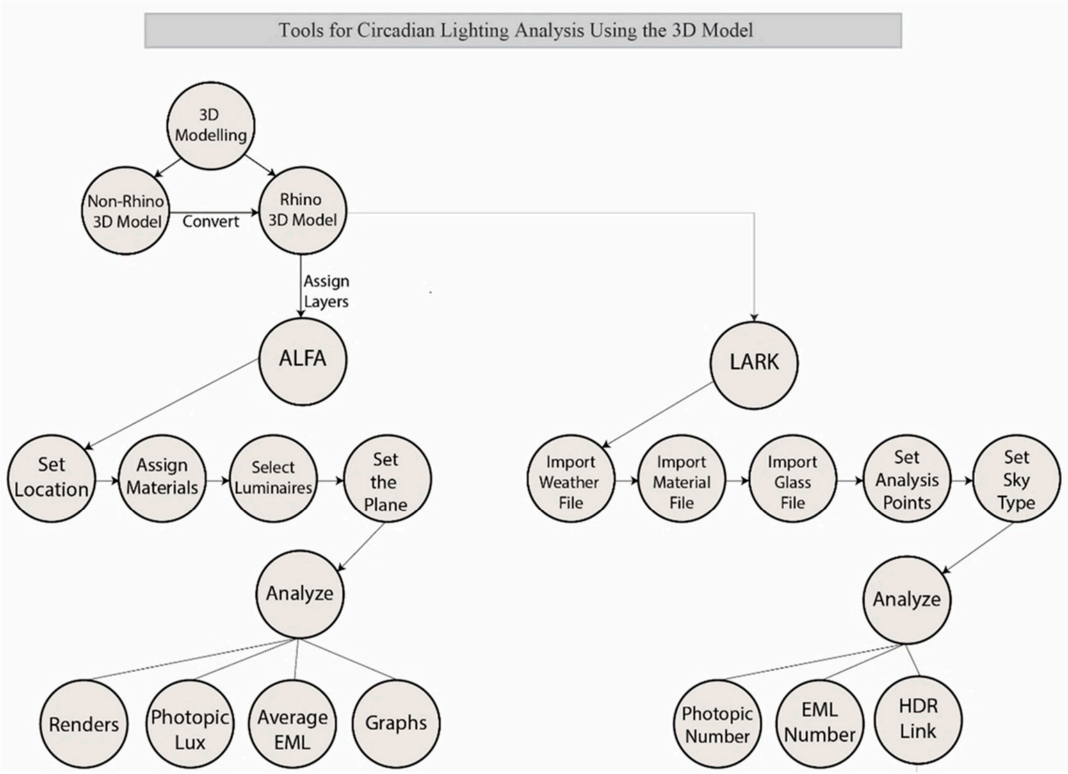

Figure 4. LARK and ALFA process map for circadian lighting analysis (source: author).

2.5. Standards and Codes

Recognizing the positive impact of natural light on human well-being, LEED (Leadership in Energy and Environmental Design) includes daylight as a certification credit. To earn points, LEED stipulates regularly occupied areas in a building must receive adequate daylight, considering factors like glare [43]. However, further investigation is necessary to determine if achieving LEED daylight points alone can provide sufficient circadian light [36].

Introduced in 2014, the WELL Building Standard emphasizes eight key areas of building design to enhance occupants' physical and mental well-being: air, nourishment, water, comfort, fitness, innovation, mind, and light. Out of the 100 features listed, 11 specifically address lighting, covering both natural and electric sources. Feature 54 focuses on circadian lighting design, and P3 emphasizes circadian lighting emulation [17].

WELL outlines specific lighting requirements for various spaces. In work areas, two options exist: maintaining at least 200 equivalent melanopic lux at 75% or more of workstations or ensuring a minimum illumination of 150 equivalent melanopic lux at all workstations. For living spaces like bedrooms and bathrooms, a fixture must provide at least 200 equivalent melanopic lux during daylight and should not exceed 50 equivalent melanopic lux at night [17].

The IES Lighting Handbook, an exemplary resource by the Illuminating Engineering Society, stands as just one among the numerous valuable references in the field of lighting engineering. Renowned for its comprehensive insights, it covers diverse topics such as design practices, controls, energy efficiency, measurements, and daylighting, catering to the needs of lighting professionals, architects, engineers, and researchers alike. While widely utilized, it serves as a prime example of how lighting standards and guidelines can be employed to ascertain lighting levels align with the specific requirements of different spaces [44].

Figure 5 illustrates the inclusion of the aforementioned data into the final framework. These additional data comprise tools utilized for circadian lighting analysis, as well as prominent and comprehensive standards and guidebooks. It is important to note the specific selection of tools and standards may vary depending on the preferences of the design team, and new ones can be added to the framework.

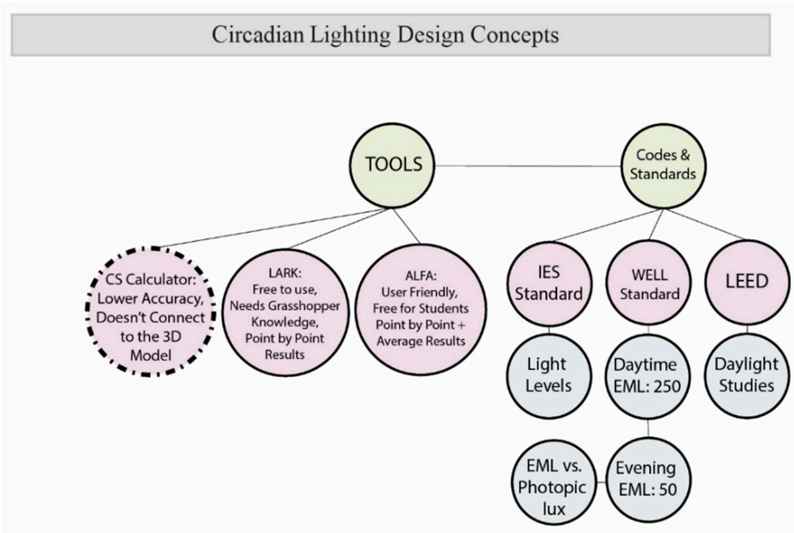

Figure 5. Part of the framework illustrated with the tools, codes, and standards for circadian lighting design (source: author).

2.6. Post-Occupancy Evaluation

The post-occupancy phase refers to a stage in the building design and construction process that takes place once the building is inhabited by its intended users. During this phase, the focus is on assessing the building's performance, pinpointing any problems or areas that could be enhanced, and implementing necessary modifications to the building or its systems.

During the post-occupancy phase, various tools are employed to assess the natural and electric lighting design. Sensors and light meters are commonly utilized to gather data. Additionally, conducting on-site visits and administering post-occupancy surveys aid in identifying deficiencies and areas for improvement (Figure 6). By comparing the results with pre-occupancy surveys, valuable insights can be gained. Computer simulations can also be employed, even for existing buildings.

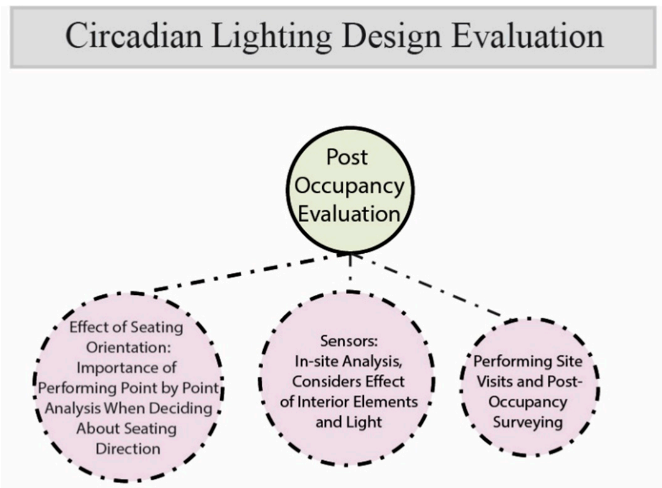

Figure 6. Procedures to perform post-occupancy evaluation for circadian lighting design (source: author).

3. Design Tradeoffs

Design tradeoffs pertain to the choices that designers must consider when crafting designs that are successful. These choices are influenced by the tacit knowledge that designers acquire through experience, allowing them to make more knowledgeable decisions. For example, a designer might opt to allocate extra resources and energy loss towards including a larger window that offers an enhanced view. This type of decision-making occurs regularly during the design process, and it applies to circadian lighting design as well.

For example, examining the connection between paint color and circadian rhythm showed intriguing tradeoffs within circadian lighting design. Although individuals may perceive cooler shades as more soothing [45–47], they can actually disrupt their circadian rhythm. Likewise, people may have a preference for dimmer, warmer lighting, but they require periodic exposure to bright cool light, especially when spending significant time indoors during the day (productivity vs. sleep and relaxation or physiological vs. psychological health). Incorporating a larger window can enhance the Circadian Stimulus from natural light, yet it may also lead to energy inefficiencies and glare (window size vs. glare and energy).

Tradeoffs can also happen when trying to choose between different tools for the analysis or the methodology for post-occupancy studies. The financial situation and the knowledge of the researcher can be the main factors when it comes to these.

These tradeoffs hold significance and should be taken into account during the design phase. To remind designers of the importance of these factors, the design tradeoffs that might occur during human-centric lighting design are introduced and added to the framework.

4. Synthesis of Design Parameters

The framework for architectural design supporting human circadian rhythm incorporates various elements and stages to ensure successful outcomes. The design process in architecture is complex due to the involvement of multiple knowledge domains. IPD is recommended by the AIA as an approach that promotes collaboration and breaks down barriers in the design process. The framework integrates the IPD stages with the concept of circadian lighting, introducing steps such as site visits, training, and pre-occupancy/post-occupancy evaluations. Setting the project goal and conducting site studies are crucial early stages, and tools are available for comprehensive site analysis. The VITALS criteria provide guidelines for circadian lighting design, emphasizing factors such as vertical light, intensity, timing, appearance, location, and spectrum. Color and psychological aspects, as well as interior design elements, also influence circadian lighting design. The framework (Figure 7) accommodates these considerations, resulting in a flexible approach that can be adapted to diverse contexts and priorities. The earlier section clarifies the intricate contexts, emphasizing that tradeoffs involve considerations spanning tools, methodologies, financial constraints, and the researcher's knowledge. This underscores the significance for designers to carefully reflect on these factors within the framework of human-centric lighting design (shown in green).

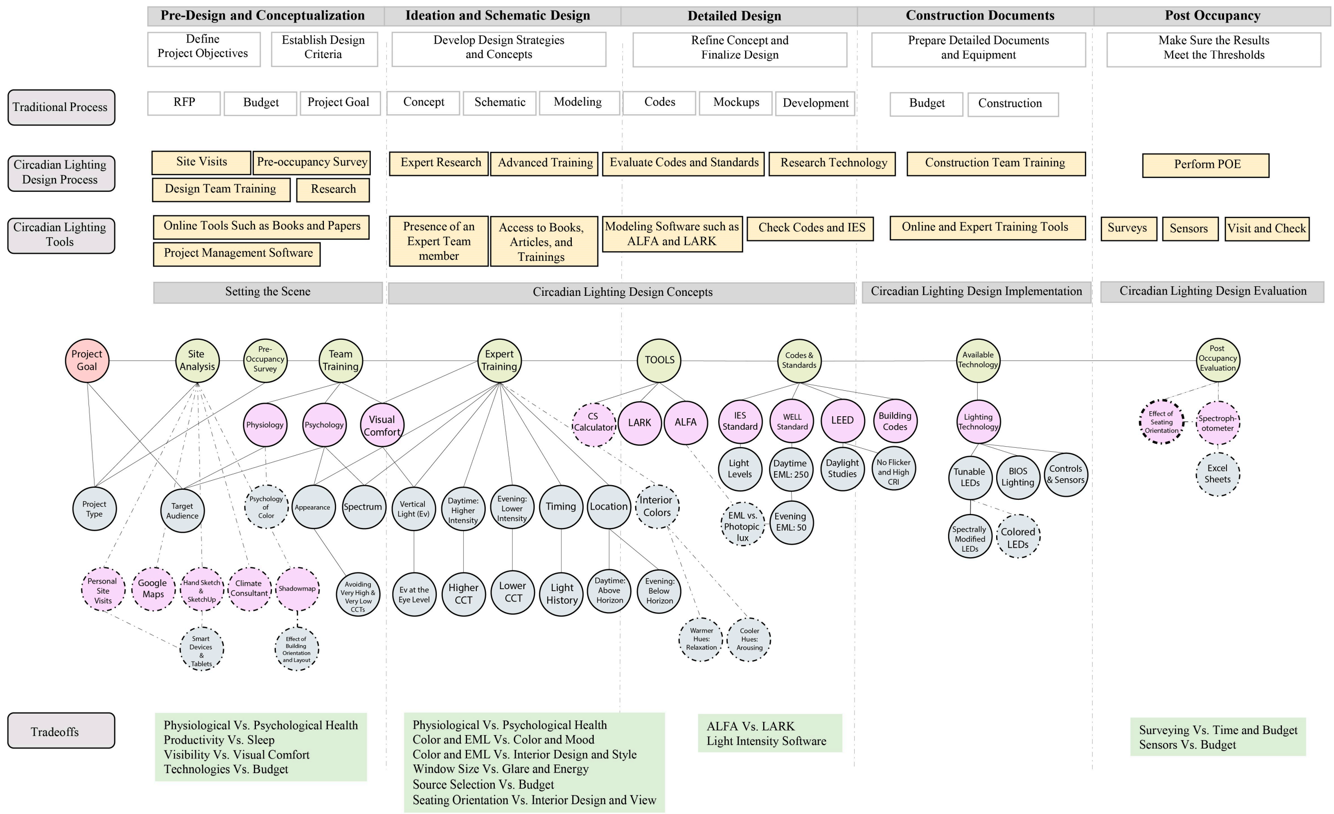

Figure 7. The design framework for circadian lighting design based on the AIA's IPD and design considerations (source: author).

5. Focus Group Presentation

In this research, a focus group presentation was conducted to gather consensus from a group of experts regarding the design framework aimed at creating buildings and spaces that promote a healthy circadian rhythm among occupants. The focus group discussion is a qualitative technique in which a researcher brings together a group of individuals to engage in a structured conversation about a particular subject [48]. The objective is to tap into the intricate personal experiences, beliefs, perceptions, and attitudes of the participants through a facilitated interaction. This method involves a purposive selection of individuals rather than relying on a statistically representative sample from the larger population [49]. The framework and the knowledge behind it were presented to a group of architects and designers at Page Company.

During the presentation, one of the researchers presented information for 25 min on the human circadian rhythm, circadian lighting design, and included relevant materials such as literature reviews and the final design framework. Additionally, a concise overview of the research goals, design principles, and knowledge domains involved in the study was provided. This office comprised designers who were originally employed by Page as well as designers who joined the office after the company acquired EYP in 2022. This unique composition makes the office an excellent choice, as it benefits from the collective insights and expertise of both teams. With a diverse pool of talent, the office is capable of designing a broad spectrum of projects.

A total of 30 designers joined and following the presentation, the participants in the focus group were given the opportunity to provide feedback on the framework. We carefully recorded their feedback using a short survey containing questions asking for their opinion on the framework and whether they would use it in their design process or not, and if they agreed with the categorization of the themes. The data were analyzed and used to enhance and refine the design framework following their suggestion for improvement. The survey questions were:

1. What is your role in the company?
2. Do you think the framework addresses all aspects of circadian lighting design in buildings? What else could be added?
3. Do you agree with the categorization of themes under this framework? If not, what changes would you suggest?
4. Would you use this framework in your design projects?
5. Do you have any other suggestions or comments?

We received ten surveys back, and nine out of ten participants expressed their satisfaction with the framework, stating that it comprehensively addressed all aspects of the issue. They also agreed with the categorization of themes, which led to the consensus that this is a useful tool they might use in their future design projects. The only participants who did not answer "yes" to the second question, which was about whether the framework addressed all aspects of the circadian lighting design in buildings, had this suggestion:

> "*I think the training should take place regularly before projects start so that the concepts can be discussed in the early predesign phase by persons already knowledgeable in the subject*."

We also received a suggestion to add "individual vs. biological needs" to the design tradeoffs. Also, one of the participants wrote about the importance of reviewing "case studies" and including everything we learned in the design "program" as well. We also received the following comment that emphasized the importance of having the required knowledge and tools for circadian lighting design:

> "*I believe circadian lighting is not getting the attention it needs in design projects because there is a lack of knowledge in the industry. Designers are unaware of how their choices and selections impact circadian metrics and improve upon them with different choices. Circadian lighting analysis helps inform the condition of the environment but there are few trained in the tools or knowledge on how to improve the design thereafter. Design-oriented and easily digestible knowledge around circadian lighting would go a long way to improve best practices done on every project*."

The statement made by the sustainability director highlighted the significance of having a well-defined design framework for circadian lighting design. Such a framework is crucial as it provides designers with the necessary knowledge and skills to effectively utilize the tools and techniques associated with circadian lighting. The framework serves as a foundation, enabling designers to navigate the complexities of circadian lighting design and harness its potential to enhance the built environment. Lessons learned from the focus group presentation were also added to the framework shown in Figure 8 in blue highlighted text.

Incorporating insights from the focus group presentation was a pivotal step in refining the circadian lighting design framework. The diverse perspectives shared by the participants, including recommendations for regular training sessions, additions to design tradeoffs, and emphasis on individual vs. biological needs, enriched the framework. These lessons learned underscore the significance of collecting and screening opinions, contributing to a more robust and refined design framework that aligns with the nuanced needs of the industry.

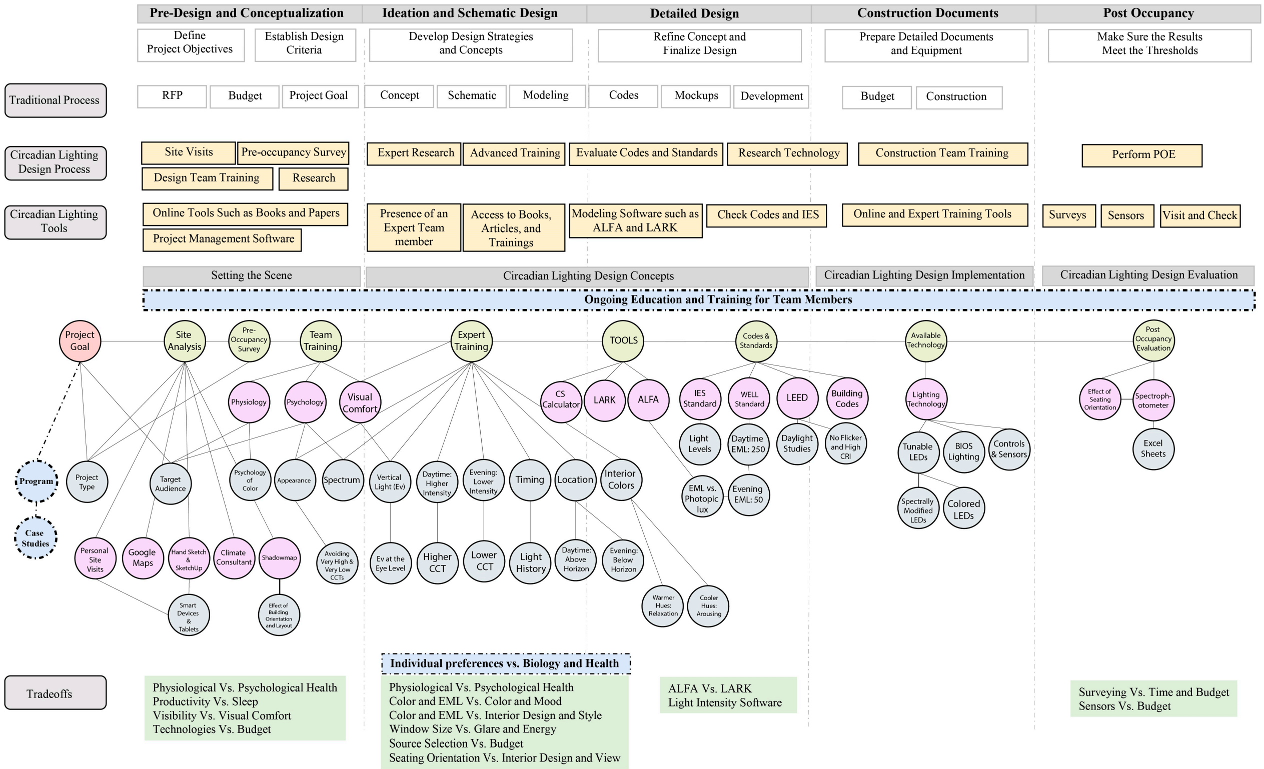

Figure 8. The final version of the framework based on the comments from the focus group. The blue highlighted text with dotted border show the items added from the Focus Group Presentation section (source: author).

6. Discussion and Conclusions

This study has significant implications for the architectural design field, particularly in relation to promoting healthy circadian rhythms and enhancing the well-being of building occupants. By incorporating circadian lighting design into the architectural design process, architects can create built environments that align with human biological rhythms and improve the quality of life for occupants.

The framework developed in this study, based on the current established knowledge, provides a structured approach for integrating circadian lighting design at various stages of the project. This approach encourages close collaboration among team members and ensures circadian lighting considerations are incorporated from the early stages of design. By setting project goals and conducting site studies, architects can identify opportunities and constraints related to lighting and access to natural daylight. These insights can inform the design process and help optimize the use of lighting and interior design to support circadian rhythms.

The study started by delving into a comprehensive review of the existing literature and methodologies related to circadian lighting design and analysis. By exploring a wide range of available resources, the study aimed to establish a solid foundation for developing an effective framework. In addition, the study examined various tools and standards that empower designers to make well-informed decisions regarding circadian lighting design. These tools provide designers with valuable insights into the physiological and psychological aspects of lighting, ensuring their design choices align with the principles of circadian health.

Furthermore, the study acknowledged the importance of post-occupancy evaluation techniques in assessing the effectiveness of circadian lighting design. By incorporating evaluation methods, designers can gather feedback and data from occupants, enabling them to fine-tune their designs and enhance the overall user experience. The results of the study were subsequently shared with a team of experienced designers, who provided confirmation of the framework's utility and effectiveness. Their feedback and validation served as a testament to the value of the developed framework in integrating circadian lighting design into the broader architectural design process. Their positive feedback toward the usability of the framework also showed it has reached its purpose to start as a beginning point for human-centric lighting design.

Overall, the circadian lighting design framework presented in this study stands out as an accessible and user-friendly tool, specifically designed for architects and designers. Its simplicity ensures ease of integration into various projects without necessitating extensive intellectual or financial investments. By leveraging the insights gained from the literature review, utilizing available tools and standards, and incorporating post-occupancy evaluation techniques, designers can create environments that prioritize the well-being and health of occupants. Additionally, each design project can help make the framework more complete. It can act as a dynamic script that expands and adapts over time, benefiting from the insights and lessons learned from each new project. Beyond its application in design, this framework also serves as a valuable educational tool in architecture, interior, and lighting design. By incorporating lessons learned from these disciplines, it ensures ongoing refinement and enrichment, enhancing its effectiveness and relevance with each successive iteration.

In conclusion, this paper underscores the pivotal role of integrating circadian lighting design into the architectural design process. The framework accentuates the importance of early stage considerations in lighting design, enabling architects to optimize solutions that prioritize circadian health. By embracing this framework, architects can craft environments harmonizing with human biological rhythms, enriching occupants' quality of life and contributing to overall well-being. Furthermore, the proposed framework holds educational potential, serving as a foundational resource for teaching circadian lighting design in architecture schools.

7. Limitations and Future Research

Acknowledging the current framework's limitations is essential. As it is based on contemporary research and existing data within the realm of human-centric lighting design—a field still in its nascent stages—continuous refinement is necessary. Given the dynamic nature of circadian lighting research, the framework has been intentionally crafted to accommodate future advancements. To address these limitations, future studies should involve presenting the framework to design studios, gathering feedback from students, and incorporating their insights for refinement. Additionally, conducting a Delphi group study can help garner consensus from a broader pool of experts in circadian lighting design. This iterative approach ensures the framework remains adaptable and responsive to the evolving understanding of circadian lighting design, thus augmenting its applicability and efficacy in forthcoming architectural endeavors.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

IPD	Integrated Project Development: Collaborative approach optimizing project results from conception to completion.
AIA	American Institute of Architects: Professional organization supporting architects through education, advocacy, and community outreach.
CRI	Color Rendering Index: Quantitative measure of a light source's ability to reveal colors accurately.
CS	Circadian Stimulus: Metric evaluating light's impact on human circadian rhythm developed by researchers at Rensselaer Polytechnique Institute.
EML	Equivalent Melanopic Lux: Measurement unit quantifying light's effect on the human circadian system for better understanding of its impact on health and well-being.
LEED	Leadership in Energy and Environmental Design: Globally recognized green building rating system promoting sustainability in construction.

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