Opportunities and challenges of integrating daylight and electric lighting principles to achieve healthy & sustainable environments in the Nordics

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Abstract. An office building in Malmö to be LEED and WELL certified, was chosen as a case study to investigate how daylight and electric lighting principles are to be integrated throughout the building design and certification processes. Along the process, challenges when considering energy efficiency and the design of healthy environments were identified, including the need for international certification systems to implement local means for the representation of health and well-being to fit Nordic conditions, where latitude and climate play a major role. As a conclusion, working closely in interdisciplinary teams is crucial when creating lighting solutions that aim to be respectful to our environment and to provide the best possible lighting conditions, fitted for humans needs.

1. Introduction
Light, both natural and artificial, plays a crucial role in the creation of sustainable architecture with people in focus. Light affects our body, physically and psychologically, and has a direct impact on our health and well-being. In the building design industry, daylight and electric lighting planning, are often treated separately, however, both disciplines address the same questions albeit through different means. As such, there is great potential for them to complement, rather than override, each other. Lighting strategies that take into consideration the person, the task and the context in the best possible way, are vital when taking a human centric and sustainable approach.

2. Literature review
Sustainable lighting design implies a design that is sustainable for the planet and all living creatures in it. A design that considers natural light, energy consumption, health, wellbeing, light pollution and the lighting system’s impact on the environment, including life cycle assessments and the optimization of the design itself.

Both daylight and electric light play a major role in creating sustainable and healthy environments. Research have shown that electric light accounts for up to 15% of the world’s total electricity use [1]. More specifically, in Sweden electricity use in lighting is estimated to account for about 11TWh corresponding to 9% of Sweden's total electricity consumption [2]. Focusing on lighting, in a technological perspective, electricity demands can be lowered by at least 50% by using existing efficient technologies [3], while daylighting integration schemes could provide further savings [4].
For daylight, studies have shown that 86% of all Europeans attribute plenty of daylight above average importance [5], and that across all age groups and cultures, there is a strong preference for daylight over electric light [6]. It has been also found that general work satisfaction is strongly determined by the presence of a window facing the exterior in the workspace [7].

It is a fact that light affects many physiological and behavioral responses, ranging from hormonal rhythms and the pupillary response, to sleep, alertness, cognitive performance and mood. [8] Despite that the benefits of daylight and electric light with focus on sustainability, health and well-being are discussed separately in many studies; most of the current certification systems, especially the most common ones on an international level such as LEED and BREEAM do not reflect this fully [9] [10]. Different certification systems around the world address quantitative requirements however lack requirements for the qualitative aspects that light contributes with. As a result of this, integrating these questions in practice is still a challenge. One of the few certification systems that addresses health and wellbeing for both daylight and electric light is WELL, which is further addressed in detail in later sections of the paper. The following sections in the paper present some of the methods that were implemented to integrate these aspects in the design process and have them as an integral part of it.

3. Method
To investigate the potential of integrating the competences of daylight and electric lighting in projects various methods were used to address these questions on different levels. These included identifying the different services that can be performed by each competence at the different stages of the design process, as well as analysing and identifying which certification systems can help in bringing the two competences closer together. Following that, a case study was used to test the workflow between both disciplines, which is described in section 3.2.

3.1 Daylight and electric light in the design process

One of the first methods investigated by daylight and lighting design specialist was to evaluate the standard building design process and identify where, when and how the question of light, both natural and electrical, should be addressed at the different stages of the process as illustrated in Figure 1.

3.1.1. Strategy for light

For the project to develop a consistent and successful lighting scheme, a strategy for light, both for daylight and electric lighting, should be defined as early as possible in the design process as shown in Figure 1. This includes defining the role that light plays in the project, the requirements for daylight and electric lighting, both in terms of quantitative and qualitative parameters, the users’ needs for light, the facilities’ opening hours, the type of tasks to be performed within the built environment, the environmental goals of the project, budget and the climate challenges of the specific context.

3.1.2. Design

Once the strategy for light is validated by all project’s stakeholders the design phase begins in which the environmental specialist will inform the design along the process of lighting design with data from daylight calculations. Furthermore, the environmental specialist informs the design with input on views, fenestrations, energy calculations, façade optimization and shading systems. Parallel to this the lighting designer develops a lighting design concept and plans the electric lighting system responding to the qualitative and quantitate needs, including a lighting control’s strategy and illuminance simulations, taking in consideration the data provided by the daylight specialist. It’s during the design phase where the potential for synergy between electric lighting planning and daylight is at the highest. This requires a deep understanding of the qualities provided by natural light within the building, the user’s needs and the limitations of the project. In this phase the coordination with the architects and interior designers is
crucial to ensure that regularly occupied spaces are placed in the best daylit areas considering daylight quantity, glare and view.

Figure 1 Daylight and electric lighting in the building design process.

3.1.3. Design & technology
In this phase, Design and Technology, the lighting design concept is further developed with the help of test lighting, illuminance simulations, LPD (Light Power Distribution) calculations, fixture specifications and placement, control schedules etc. In this phase the environmental specialist runs final daylight calculations, energy simulations, and fine tunes the shading system and facade specifications. During the construction phase, electrical lighting is programmed according to the daylight studies run earlier in the project. Different lighting scenarios will be set and followed up once the building is in use to make the necessary adjustments after user needs and preferences.

3.2 Case study: office building in Malmö
The evaluated case study used in this investigation is an office building in Malmö (55°36'21.13"N) to be both LEED 4.1 and WELL v.2 certified, in addition to fulfilling the local regulations in Sweden for daylight (Boverkets byggregler, BBR). The building consists of 9 floors including a basement, with a total area of ca 7 700 square meter of office and facility areas that include a restaurant and roof terrace.

3.3 Sustainability and well-being: daylight and electric lighting planning
As previously mentioned in the literature review, most certification systems treat daylight and electric light separately, except for the WELL certification system that considers both of them in the same section and cross daylight and electric lighting requirements in the feature of circadian lighting. Based on this, the parts under the light feature of the WELL certification were evaluated and implemented in the case study aiming to assess how the different features can influence decision making towards the creation of healthier environments. The light feature in WELL is composed of eight sections, two of which are pre-conditions and six that are optimizations. Each of the eight include several sub-categories under each feature. This paper focuses on presenting six out of the eight points that were studied more in-depth as they represent the most challenging ones which are described in the following section. L02 Visual Lighting Design and L06 Visual Balance are the two features not included in this paper.

3.3.1. Ensure Indoor Light Exposure: Spatial Daylight Autonomy
As a precondition in WELL, this feature ensures that spaces receive enough daylight, and this can be verified by meeting the demands of one of three alternatives:
   a. $sDA_{200,40\%}$ (Spatial Daylight Autonomy) is achieved for at least 30% of regularly occupied space.
   b. 30% of all workstations are within 6 m [20 ft] of transparent envelope glazing. Visible light transmittance (VLT) of transparent glazing is greater than 40%.
   c. Transparent envelope glazing area is no less than 7% of the floor area for each floor level. VLT of envelope glazing is greater than 40%.
In this case study, options a and b were investigated.
3.3.2. Circadian Lighting design
The circadian response of humans to light is dependent on the light that enters the eye and on factors such as spectral properties of the light, light intensity, brightness levels, duration and timing of exposure. Science has proved that light has the immediate effect of increasing subjective and objective alertness [8]. Lighting for the circadian system is an optimization within WELL that aims to ensure a lighting system that provides sufficient EML (Equivalent Melanopic Lux) measured on the vertical plane at eye level of the occupant to support circadian stimulation, in all regularly occupied spaces. Thresholds for EML values are conditional to the achieved points in feature L05: Enhanced Daylight Access and thus can vary between 120-240 EML.

3.3.3. Glare control
This feature requires that the building either has exterior shading for all envelope glazing (except atriums or lobbies) and that it is controlled by the occupants or automatically. The second option is that ASE$_{100,250}$ is achieved for no more than 10% of regularly occupied space. Considering that it was decided that the requirements for sDA were not going to be considered, the ASE requirements were not simulated.

3.3.4. Glare from electric lighting for all spaces
This feature is set to meet one of the four alternative requirements to avoid glare from electrical lighting in regularly occupied spaces. For the case study we decided to use alternative b – Unified Glare Rating assessments, with UGR of 19 or lower for luminaires installed at a height of 5m or lower and UGR 22 or lower for luminaires installed at a height greater than 5m. UGR was digitally simulated for all lighting positions to ensure that the recommendations were met. Nevertheless, we did identified contradictions between the circadian lighting requirement and the UGR max allowable values, that will be further explained in the next section of this paper.

3.3.5. Enhanced Daylight Access: ensure views
It includes three options:
   a. If at ground floor, distance from fenestration to roadway is at least 7.5 m [25 ft] from the exterior of the glazing.
   b. View factor of 3 or greater.
   c. Views with a vertical view angle of at least 30 degrees from occupant facing forward or sideways provide a direct line of sight to the ground or sky.

Points b and c were considered. Using Rhino as a modelling program, a Grasshopper definition was made to automate the analysis process for point b to be able to evaluate the vertical view from the analysis points through multiple windows. This was done to speed up the analysis considering a 3D evaluation instead of a 2D evaluation using sections in the building, and to make sure that the view out is not only evaluated considering the closest window.

3.3.6. Electric Light Quality: ensure color rendering quality and manage flicker
This feature requires the project to consider characteristics of electric light used in the space such as color rendering, color quality and flicker. Generally speaking electric lighting should meet higher CRI values than those stated in the European standard (EN 12464-1). When it comes to managing flicker, all electric lights (except decorative lighting, emergency lights and other special-purpose lighting) used in regularly occupied spaces should meet one of the two alternative requirements for flicker. When it comes flicker they key lies in the quality and type of drivers used to feed the luminaires, thus for the case study drivers where specified to comply with requirement of the WELL certification. With regards to the color rendering quality, all specified equipment complied with a CRI above 90.

3.3.7. Occupant Control of Lighting Environments
This feature requires the project to implement innovative lighting strategies that take into account personal preferences of users as well as their interaction with the physical space.
When it comes to Part 1 Enhance Occupant Controllability, ambient lighting systems in regularly occupied spaces should meet the following requirements:

a. Light systems are tunable and automated to meet the occupants’ circadian and visual requirements.

b. Occupants have control of light levels, color temperature and color of electric light in their immediate environment and can override automated settings for at least 30% of operating hours.

In part 2 of this feature, Provide Supplemental Lighting, all spaces should comply the requirement of supplementing additional fixtures to users, upon request, that are capable increasing the lighting levels on the task surface to at least twice the recommended light levels, are free of cost upon request, which is met within eight weeks of request.

4. Results
The results section is divided into two main parts, the results for the daylight points in WELL and the results for the electric light points.

4.1 Daylight

4.1.1. Ensure Indoor Light Exposure: Spatial Daylight Autonomy
The following figure shows the results of the Daylight autonomy and the percentage of compliance for the sDA in plan 1 of the building each zone in part of the floor plan excluding the effect of dynamic shading. The maximum sDA reached was 55% without shading, which means if the shading is accounted for in the simulation it will be hard to meet the sDA requirement. As a result of this point b in this part was considered instead. It was identified however that there is a big gap between points a and b considering that point a is very hard to achieve and would require close consideration of the properties of the dynamic blinds used in the building, while point b can be used to inform the design at early stages and could possibly be achieved.

4.1.2. Enhanced Daylight Access: ensure views
The following figure shows the result of this requirement in part of the building on plan 3. The results were divided into three categories, starting with a vertical view point from the centre of each circle and looking towards the window vertically in two perpendicular view directions. The results show the points that met the requirement, the ones that did not, and the points that did not fulfil the view requirement. The results showed that most of the points fulfilled the requirement, and that was primarily because this analysis was done for plan 3 which had less obstruction angles to the neighbouring buildings. The building therefore meets the requirements in point C.

This requirement is useful in informing the design regarding the placement of the different work stations, the depth of the regularly occupied spaces, as well as the relation of the windows with respect to the seating areas. However, by analysing the results, this feature could be further improved by adding a requirement regarding the view quality as well. Currently in WELL, point b requires a view factor of
3 or more, however according to the definition of the view factor [11], the quality of the view is not included in this assessment.

![View requirement met]

- The view requirement is met

- The view requirement is not met

- The point does not fulfill the view requirement

![Figure 3 view analysis for plan 3]

4.2 Electric Light

4.2.1 Electric light: circadian lighting and manage of glare

A lighting design concept was developed in response to the site-specific conditions, user’s needs, the design features, taking in consideration the project’s requirements to meet the WELL and LEED certification. Aside from the pure technical requirements, such as high CRI values, management of flicker and illuminance levels on the horizontal planes complying with EN 12464-1, the most challenging part of the design was to provide a comfortable lighting system, in regularly occupied spaces, that complied with the WELL features L03, L04 and L08. EML values were measured at 45cm above the work plane on a vertical plane simulating the light entering the eye of the occupant. (Figure 4) Illuminance values measured at this point are then multiplied by a coefficient (R) that is calculated based on the spectral distribution of the light source under which you are measuring. We used the IWBI excel sheet provided by WELL to identify the correct coefficient. On tunable white fixtures we used the R value of LEDs 4000K. Full spectrum white light with a CCT of 2700K for example, has a lower coefficient than a colder full spectrum white light of 4000K due to its blue-enriched part of the spectrum, which implies that higher amounts of light will be needed from warmer white lighting than cooler white lighting to achieve equal EML values.

Early in the design process we identified the contradiction between having high amounts of light at eye level and avoiding discomfort glare, being one of the biggest challenges when it comes to both ensuring visual comfort and circadian lighting.

After running several simulations, we identified that digital tools are not fully reliable when assessing glare in the case of EML assessments. With the aim to ensure an optimal solution we performed 1:1 test (Figure 5) to compare different light fixtures and placements, visually and measure in real life. Our investigation lead us to identify pendant luminaires as the most suitable solution for circadian lighting, due to the proximity to the users, which guarantees better glare control at higher light levels.
Following the ASHRAE 90.1 LPD requirements and using the space-by-space method, the majority of regularly occupied spaces with EML values between 180-240 complied with the w/m² allowance, with results ranging from 5.4 - 10 w/m². Small cell offices with two workstations were the exception with an LPD result of 16w/m², though in these rooms the values at eye level were above 240 EML.

4.2.2 Electric light: Occupant Control of Lighting Environments
We addressed WELL feature L08 part 1 by designing a strategy that allowed users to override the intensity and Correlated Color Temperature (CCT) settings in regularly occupied spaces. We investigated the alternative of controlling the lights via a Bluetooth through the user’s smart phones as well as adding an additional cord or button placed in the luminaire itself. (Figure 6) These two alternatives were left as a proposal to be further developed in the coming phases of the project. Solutions where circadian lighting is mounted close to the users, like in the case of our case study, are to be preferred not only due to comfort advantages but also energy consumption.

5. Discussion
Regarding integrating Daylight and Electric light, feature L03 is the only feature in WELL that demands a synergy between daylight and electric lighting when it comes to defining the EML values required for achieving the different points in this feature. This implies that a building with ‘better’ daylight requires lower illuminance levels at eye height than a building that has ‘poorer’ daylight to achieve the same points. This is a step forward in making an effort to ensure better daylight inside buildings that can endorse circadian stimulation and reduce energy consumption from electrical lighting.

The relation between horizontal illuminance and vertical illuminance when analysing circadian stimulation from ceiling mounted luminaires was studied. It was observed that to achieve the lowest value of 120EML at a colour temperature of 2700/3000K, which is largely used in the Nordic countries,
horizontal illuminance at work plane height should reach levels above 600-650lux and over 1200lux to achieve the highest value of 240EML at the same CCT. Considering that 650lux surpasses the 500lux from the EU standard for visual performance in working spaces, it implies that achieving 120 to 240 EML from ceiling mounted luminaires will ultimately have a great impact on the energy consumption of the lighting system, when feature L05 Enhanced Daylight Access is not achieved. This stress the importance of working in interdisciplinary teams that can ensure a lighting solution that provides high-quality and quantity of light with minimal energy use.

6. Conclusion

With the rising need in meeting the 2030 Agenda, coupling daylight and electric light is of great importance directly impacting multiple Sustainable Design Goals SDG(s), such as Good Health and Well-Being, Responsible Consumption and Production, and Affordable and Clean Energy. These goals were used as a reference when working with the case study. The integration of daylight and electric light is crucial when focusing on wellbeing and energy efficiency, however more work is needed in current certification systems to reflect that. The studied case can be considered successful as through the set workflow the specialists were able to inform the design, optimize the building and create a lighting scheme that complies with all the WELL and LEED features. However, the WELL certification demands a different workflow along the building design process in comparison to projects aiming for LEED only, challenging the status quo of how design decisions are to be taken between property owner and tenants, as well as redefining the role that daylight specialist, lighting designer, electrical consultant, architects and interior designers play along the lighting planning process. In addition to that, when trying to achieve circadian lighting with good glare control and optimal energy performance, lighting should be coordinated with the placement of regularly occupied spaces and can no longer be developed as a basic and homogeneous layer of light across floors, without jeopardizing energy performance and visual comfort. The study also revealed a big gap between local and international regulations and certifications, including inapplicable thresholds for the Scandinavian context, challenges when combining different certifications in one project, and metrics for circadian lighting assessment that compromise visual comfort and energy consumption. Therefore, in conclusion, there is a need for international certification systems to implement local means for the representation of both daylight and electric light, health and well-being and reflecting interdisciplinary workflows both globally and in the Nordic context. Considering that LEED and WELL are international certification this approach can be scalable to all types of projects where people spend a big part of their time indoors.

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