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I. Introduction: Sustainable Lighting Design

The aim of this paper is to provide a step-by-step design and decision making processes towards an energy-efficient and user accepted lighting system. The past few decades have challenged our lighting designs in architecture as to whether they are environmentally and ecologically correct. Are we considering the advantages daylighting can have on the psychophysical and energy performance of our buildings? Do we even have the proper frame-of-mind towards the integration of daylighting into our designs?

In a recent and highly respected review from some of our world leading researchers (names intentionally withheld) it is stated that: “daylighting is the use of light from the sun and sky to complement or replace electric light”. The author suggests a subtle but extremely important shift from this line of thinking. Are we stating that daylight is possibly here to enhance our electric lighting systems? Perhaps we might consider, from an existentialistic viewpoint that daylight was here first. An integrated lighting design might be one which begins with the onerous task of discovering how and where daylight enters our spaces.

After tedious refinements and an understanding of daylight entry there might be a discovery as related to the quantity and quality of this light and how it might be controlled or supplemented. We now have a completely different paradigm where daylight zones are discovered, controlled and possibly enhanced through an electric lighting system and its associated controls. The difference in our approach is to design for and with daylight first.

As stated in a European text on daylighting in architecture there are three ways to convince designers of the advantages to be gained by improving daylighting performance on their projects (Baker et.al., 1998):

1. showing possibilities through case studies
2. providing analysis and information regarding the lessons learnt and how things can be improved.
3. make available to architects tools that can assist them in the design an analysis of daylight buildings.

Design ideas come from a stored repertoire of building solutions experienced. Those which appear to offer results are remembered and perhaps even refined and reformulated. It is useful to make reference to such architectural precedents that have provided successful solutions of lighting. Simplified design tools are useful usually after the event of design has taken place. Even the most simplified tools will be used to evaluate a design but rarely, if ever, used in the initial design sketch. It is therefore, suggested that checklists or a reminder of 'criteria to be considered' be provided for the designer before and after this creative process. Most other evaluation tools will enter the design process in the stages of lighting design refinement.

Table I is an outline towards goal setting for a successful lighting design. It can be used as a checklist to consider the multiple processes involved in lighting a space. The intention is to consider all the possible methods of daylight first before resorting to electric lighting which is primarily put in place to compliment daylight.
ARCHITECTURAL & TASK LIGHTING QUALITY

Desired illumination level on task area
Appropriate lighting distribution and definition
Optimised visual contrast and minimisation of glare

<table>
<thead>
<tr>
<th>DAYLIGHTING</th>
<th>ELECTRIC LIGHTING</th>
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</table>

**Room Criteria:**
- Room Dimensions
- Room Geometry
- Surface Treatment (Texture)
- Surface Reflectance Level
- Surface Colour

**Daylighting Conditions:**
- Sky Condition
  - (Clear, Party cloudy, CIE overcast)
- Season (Summer and Winter solstice)
- Time of Day

**Window Location:**
- Consider orientation
- Sidelight (window)
- Clerestory
- Skylight

**Window Treatment:**
- Shading (interior / exterior)
- Glass Type (clear, tinted, reflective)
- Visible light transmittance
- Glass Shading Coefficient (SC)
- Spectral distribution

**External Factors:**
- Adjacent Building Orientation
- Surface Reflectance and Colour
- Ground Reflectance
- Other Obstructions

**Light Sources:**
- Incandescent Lamps
- Fluorescent Lamp
- Low Pressure Sodium Lamp
- High Pressure Sodium Lamp
- Metal Halide Lamp
- Light Emitting Diode (LED)

**Light Distribution:**
- Polar Curves
- Direct / Indirect sources
- Fixture design

**Light Colour:**
- Light source
- Fixture surface colour
- Filters

**Controls:**
- Fixture Layout Strategies
- Schedule Strategies: timing
- Dimming
- Switching
- Adaptive Control Intelligence

Table I  Considerations Towards Effective Lighting Design

A. Historic precedence on integrated lighting design

Natural lighting of a space has always played a dominant role in architecture. There are generally two reasons for lighting a space; first to reveal the architecture (structure) of the building and second to provide visual comfort and functional illumination (Baker et.al., 1998). Interestingly enough an optimal use of day lighting occurred at a time in history when energy was cheap but when artificial lighting was just being developed. At this point in history artificial lighting was used to enhance and contribute to areas of illuminance deficiencies.

In the late 19th and early 20th century many of the office spaces which were similar to our present office functioning were designed to provide daylight. Such buildings allowed for
courtyards or atrium type spaces to illuminate adjacent offices. The Chile Haus in Hamburg, Germany, designed in the 1930's is such an example (Figure 1). In this case, what appears to be a solid massive building, courtyards are incorporated serving several functions; daylight, ventilation and fire access, for a multi-storey building.

Figure 1  The Chile Haus in Hamburg, Germany – plan and photo (P. Parlour)

B. Assessment of lighting integration at the programming stage

The above example is a building which incorporated several environmental and service criteria through its simplified design of courtyards, creating a narrow plan design. It is essential to consider lighting design as integrated along with other services of a building. At the programming stage, an assessment on the value of daylight needs to be acknowledged through cost benefits and energy efficiency. It must be realized that daylighting is also a beneficial design strategy for other reasons providing:

- comfortable and pleasant daylighted spaces increase occupant and owner satisfaction and reduce absenteeism
- pleasant daylighted spaces may lease better-than-average rates.
- comfortable daylighted spaces have lower tenant turnover rates.
- daylighting is the most cost-effective strategy for reducing an associated electric lighting and cooling energy of 30-40%.
- daylighting contributes to a more sustainable design approach.

(Lawrence Berkeley National Laboratory: Tips for Daylighting with Windows)

Figure (2) provides a diagram outlining a suggested process at the programming or planning stages of a project. The objective is to provide a cost benefit and energy feasibility study at this stage in the project. It is essential that some numerate result be provided to establish goal and target settings for daylighting against a basecase building. This process can occur prior to any design concept of the building.
Figure 2  Daylight Integration into a Project at the Programming Stage

Goal setting and target analysis can be provided through computer programs or through simplified hand calculation methods. One of the tools familiar to the author and highly capable of providing the interactive effects of daylighting regarding glazing type, dimming control, number and size of window and skylight openings as well as the reduction of HVAC cooling loads is through ENERGY-10. This program is more than adequate at setting design targets at the programming stage of the project. Its results on operational energy could be used for initial feasibility and cost-benefit analysis.

C. Capital gains, energy reduction and cost benefits

Figure 3  Life-cycle Energy of Electric Lighting (Bradshaw, 1993)

The evidence for a daylit building is supported through numerical means. Additional arguments from a life cycle energy analysis point of view may further substantiate the use of daylight (Figure 3). For every single unit of useful lighting to a space it takes over 98% units of energy to produce it! From an ecological and sustainable standpoint, this argument by itself, may provide enough reason for pursuing a daylit building design. Having stated this, it is important to be able to numerate and estimate actual energy and cost-benefits for a particular lighting design at the pre-design stage.
Figure (4) illustrates a resulting output from the ENERGY-10 program for a particular project, a Melbourne primary school building. Illustrated is one out of several analytical graphs which could be produced by ENERGY-10 for examining the potential influence daylighting could have among several other energy efficient strategies for a building. The statement for daylighting is often made quite clear in such an analysis and the targets for energy savings through daylighting over that of a base-case building can be set at the programming stages of a project.

**RANKING OF ENERGY-EFFICIENT STRATEGIES**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Savings %</th>
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<tr>
<td>Insulation</td>
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<td>Daylighting</td>
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<td>Glazing</td>
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<td>Duct Leakage</td>
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<td>Air Leakage Control</td>
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<td>Solar Heating</td>
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<td>Shading</td>
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<td>Thermal Mass</td>
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*Melbourne School  
BaseCase = A$ 8327*

Figure (4) The Ranking of Several Energy-Efficient Strategies in Terms of their Effectiveness

In the forthcoming example (Figures 5 and 6), an educational building with an east-west axis was considered, as a case needed to be made for the implementation of daylighting integrated with the shading, lighting control and the mechanical system sizing.

Figure 5 provides a comparison of the base case (non-daylit building) against an energy efficient solution. It is evident that substantial savings are provided in the ‘Lights’ category.
through daylighting and that these effects are further realized in the reduction of ‘Cooling’ energy. The ‘Heating’ category is somewhat reduced, but an energy efficient lighting system produces less heat and therefore may require more heating. Figure 6 illustrates the effects external shading devices and lighting control have on the peak loads of the mechanical system. The circled values indicate the two different (north and south) zones of the building. It is noted that the values are virtually identical in peak load, implying that the mechanical system selection would be the same. This example illustrates the benefits of a total integrated design approach, involving daylighting, glazing system selection and size, dimming control, shading and mechanical system sizing, right at the pre-design and programming stages of a building. These targets should become part of the goal-setting in the brief.

II. Designing for Daylight

A. Recognition of daylight entry into the space: (façade & building envelope)

The most important design aspect of lighting integration is probably the understanding from where daylight enters the space. The previous Table I suggests that there are typically three distinct categories from where daylight enters a space: window, clerestory and/or skylight. Each of these categories needs to be evaluated according to the type and quality of light they offer. Typically the objective is to utilize the light form the sky (skylight) and to diffuse the direct luminous component the sun. Once this has been accomplished it is advantageous to consider the methods of bringing this diffused light into the space.

Side-lighting or bringing diffused light in through a window is considered to be effective at 1.5 times the floor to glazing height. Through the use of higher interior floor to ceiling heights and a clerestory light-shelf or light guiding portion in the façade this ‘glazing height to daylight penetration’ can be extended to 2.0 and even 2.5 times the overall glazing height (Figure 7).

Figure 7 suggests the division of the façade into a daylight clerestory and a vision / view portion be considered for maximizing the opportunity for daylight into the space.

Some very useful design guidelines for commercial buildings are provided within the Lawrence Berkeley National Laboratory – Tips for Daylighting with Windows under the Envelope and Room Decisions section (http://eandle.lbl.gov/btp/pub/designguide/). Figure 7 suggests the division of the façade into a daylight clerestory and a vision / view portion be considered for maximizing the opportunity for daylight into the space.
The diffusing of direct sunlight at any envelope penetration is a very important consideration for the effectiveness of daylight entry into a space. If the lighting levels are too intense then there will be potential glare problems and a rejection of daylight by the occupant. In climates of overheating, diffusing the direct solar component before it comes in contact with the building envelope is very beneficial. This can be accomplished through external shading and light diffusing devices. An excellent example is the shown in the placement of a metal screen above an opal translucent skylight used in the Park Ridge Primary School, Melbourne, Australia (Figure 8).

Figure 8  Park Ridge Primary School with Screened Skylights – designed by Taylor Oppenheim Architects with K. Poulton lighting consultant

The previous examples are only a few from many ideas used to produce diffuse daylighting for a space. Several of the listed texts and sources as provided in the reference list should be sourced for additional information and rules of thumb.

B. Brainstorming Concepts on Lighting

It is not ludicrous to consider the design process as one which is inclusive of ‘daydreaming’ or brainstorming. In a recently designed university building several brainstorming ideas were considered with regards to lighting. The cross-sections as shown in Figure 9 illustrate a before and after solution with regards to daylighting concepts as integrated with electric lighting design and control as well as comfort. Unfortunately the ‘before’ case is a quite typical solution for an Australian building. Brainstorming for a pre-determined proportion and building volume occurred very early in the lighting consultation stages of the project. In hindsight and in reference to developing a ‘roadmap’ such tasks may be considered after a pre-design or project brief/programming phase. At this stage, the possible locations of window openings, daylight distribution systems, glazing material and type, etc. are considered together with the electric lighting concept.

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Figure 9  Possible lighting concepts for a pre-designed office space
For the above example the brainstorming process continued through to the luminaire placement, control and design itself. A direct-indirect fluorescent lighting fixture was designed with the upward power distribution into a ‘batwing’ shape (Figure 10). Such a photometric distribution is effective at distributing the light uniformly across the ceiling plane and voids distinctive areas of contrast. This lighting fixture has an 80 percent LOR (light output ratio) efficiency.

Figure 10 A Direct-Indirect Fluorescent Lighting System for Maximum Light Distribution

III. Examples and Case Studies of Integrated Lighting Design

The following studies are examples of daylight taking on a primary role in the project brief requirements. Unlike the typical approach taken up by electric lighting consultants, each space is designed first to achieve an optimal daylighting performance. Only after achieving a daylighting scheme was the design development of electric lighting considered. It was further realised that the electric lighting layout and control strategy was designed in terms of complimenting the daylighting concept. Several benefits of this altered approach to lighting design are recognised through the provided case studies.

A. Electric Lighting Integration: working with the daylit zones

Lighting layouts for offices generally provide a perimeter, centre and interior zone of daylight. Figures 11 and 12 provide an example of the electric light integration together with a perimeter daylit zone. If a proper glazing system is selected which has a high visible transmittance and low Shading Coefficient (SC) a result as indicated in Figure 11 is achievable. The next step is to introduce a lighting control system which is integral to this daylight performance (Luther, 1997). A perimeter row switching (or dimming) concept is presented in Figure 12. Here upon entry to the space the interior row automatically is switched on while the perimeter row is left off. This interior row could also be dimmed to a set level. The user has control over the switching of the perimeter row and can switch them on if they choose. Studies have proven to be about a 30% electric light reduction from that of a non-perimeter row switching concept (Luther, 1998).
B. Electric lighting strategies: the selection of the light source

The electric lighting strategy provided in Figure 10 illustrated a light source that complemented and mirrored the effects of daylight entry. Several other reasons for selecting a light source might be its ability to allow for dimming and its colour rendering capabilities.

In the next example (Figure 13) an integrated lighting layout for an open 1000m² studio space is introduced which was designed considering daylighting patterns first. This space had to meet several lighting requirements and expectations from its users. The need to separate lighting zones into corridors and studio spaces, provide on/off switching to blackout areas, dimming to daylit zones achieving a lighting balance, demanded a flexible and adaptable lighting control system. The decision was made to employ the new DALI system which permitted individual control and programming to each of over 120 light fittings.
Figure 13A is the daylight result under a partial cloudy sky (in Winter) for the original space which only had the west facing windows. For Figures 13 B&C a clerestory opening and interior zone skylight was introduced (Figure 14). The resulting difference with the inclusion of clerestory and skylight openings, is clearly evident, in producing daylight zones.

Figure 14 Cross-section of the studio with existing and proposed envelope openings.

C. Lighting control systems: obtaining a balance of light
Creating a lighting balance within large open spaces together with daylight can be a challenge. For a computer dominated open office environment daylight can become a liability when levels are too high and the light consists of direct sources upon the screen. It is recommended here that lighting designers consider the assistance and complementing of electric lighting systems. This advice implies that we do not design for minimum daylight factors (DF) under an overcast CIE sky, but rather obtain results under partial cloudy or average sky conditions. When considering daylight extremes it is suggested that we investigate both ends of the situation; a complete overcast as well as a clear day sky.

The results of the next example (Figure 15) produced a very successful example for an open office with a heavy use of computers. In this case, non-direct (south facing) sky light enters the space through clerestory windows. The selection of the glazing type, location and opening size was optimized to allow for a reasonable, but not daylit dominated result. This produced a selective daylighting result which relies upon the electric light source to top it off.

DAY TIME – CLEAR DAY
Time: 12th JUNE 12:00noon
Daylight only
Average: 251 lux
IV. Conclusion
This design guide note has introduced a possible approach to integrated lighting design. It has demonstrated the need for daylight integration into our present lighting design methods. Although there are many issues to be undertaken by the designer, the ideas that reinforce and support daylight at the beginning stages of any project, are vital to ecological sustainable design. This note has emphasized that in order for an integrated and effective lighting design to take place the following should be considered:

- Learning from the precedence of good integrated lighting examples.
- Establishing the daylight entry provided by the envelope: (windows, clerestory, skylight)
- Investigating how daylight is controlled through the building envelope and interior design.
- Numerating and quantification at the pre-design and programming stages of a project.
- Setting targets in the project brief for daylight integration and control.
- Brainstorming on effective and integrated lighting concepts.
- Examining daylight patterns throughout the year for various sky conditions and periods.
- Studying the appropriate light sources, distribution and layout for the space
- Producing a flowchart for integrated lighting control strategies.

References
Julian W.G., 1999, Lighting: Basic Concepts, Department of Architectural and Design Science University of Sydney, University of Sydney Printing Service
Lawrence Berkeley National Laboratory – Tips for Daylighting (http://eandle.lbl.gov/btp/pub/designguide/)