Daylighting Handbook I

Fundamentals
Designing with the Sun

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Designing with the Sun

Fig 1.1 Chapel of St. Ignatius, Seattle, Washington, by Stephen Holl, 1997

Photo: Chris Meek

Preface

Welcome to the *Daylighting Handbook I*. This book is organized into two parts, *Fundamentals* and *Designing with the Sun. Fundamentals* serves as a general introduction to daylighting design, its implementation and availability. *Designing with the Sun* covers a series of design approaches and tools.

The complete *Daylighting Handbook* will consist of two volumes. Volume II is expected to become available in 2015 and will comprise of chapters II-9 to II-18. The handbook incorporates lessons learnt during nearly two decades of research and a decade of teaching daylighting concepts to architectural students and practitioners at MIT, Harvard and McGill. This experience lead me towards a design framework for daylighting that encourages the complementary use of rules of thumb, simulations and physical scale models.

My gratitude goes first and foremost towards my wife Diana for giving me the time to work on this extended project. I am equally thankful to MIT and Harvard for providing me with the resources to sustain this effort. Text and figures of Volume I are the outcome of a thoroughly pleasant collaboration with my editor Ria Stein and graphic designer Yoshiki Waterhouse. Substantial contributions were also made by Eduardo Berlin, Alstan Jakubiec, Jeff Niemasz, Tarek Rakha, Andrew Sang and Dan Weissman. My special thanks go to Peter Boyce, Andrew Marsh, Jeff Niemasz, Les Norford, Steve Selkowitz and Kevin Van Dem Wymelenberg for reviewing draft versions of selected chapters.

I made every effort to ensure that the information presented are accurate and relevant. Should you nevertheless detect errors, typos or have divergent opinions, feel free to share them with me at tito@mit.edu.

Christoph Reinhart
Cambridge, December 2013

Photo: Andrew Sang

Fig 1.2 Extension Cambridge Public Library, Cambridge, Massachusetts, by William Rawn Associates, 2009

1 Introduction

Daylighting and Sustainable Design

Daylighting is the controlled use of natural light in and around buildings. The term is a derivate of the noun *daylight* and implies a process by which direct sunlight and diffuse daylight are reflected, scattered, admitted and/or blocked to achieve a desired lighting effect. As discussed in chapter 2, the benefits of daylighting range from reducing energy consumption for electric lighting and subsequent cooling loads to improving occupant comfort and health, a view to the outside and enhanced design aesthetics. At the same time there are dangers associated with admitting too much daylight into a building such as overheating, glare and lack of privacy. Balancing these effects requires careful design.

Given that any nonopaque element in a building envelope "daylights" the building's interior, the concept of daylighting is as old as architecture itself. The role of daylight being the default daytime lighting solution for building interiors remained mostly unchallenged until the widespread deployment of affordable fluorescent light from the early 1940s onwards.[1] The introduction of affordable electric lighting and mechanical ventilation allowed floor plan depths to grow and windows – being freed from having to provide light and fresh air – could instead serve other architectural needs from design aesthetics to views.[2] Daylight became dispensable. The climax of this development may have been the windowless classrooms from the late 1960s, which were specifically designed to prevent students from being "distracted" by views to the outside.[3]

Following the oil crisis of the 1970s, daylighting briefly enjoyed renewed attention from governments, researchers and some designers who promoted a more efficient use of energy in buildings. During this period daylighting tended to be mainly viewed as an energy efficiency measure, a means to "replace" electric lighting and to reduce cooling loads. The first photocell-controlled electric lighting systems were thus designed with limited attention to occupant comfort, were frequently cycled on/off and provided inconsistent lighting levels on task areas. As a consequence, systems were often disabled by the occupants. Similarly, fresh air supply rates in many commercial buildings were simply reduced in the name of energy efficiency, a practice which famously backfired with the widespread appearance of sick building syndrome, a family of acute health and comfort

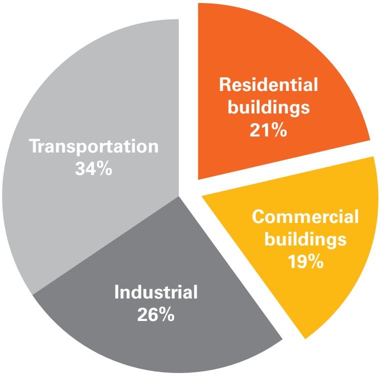

Fig 1.3 US CO_2 emissions by sector (Source: US Energy Information Agency)

effects that appear to be linked to time spent in a building.[4] With such negative connotations associated with energy efficiency measures in buildings, including daylight, it is hence not surprising that interest in those technologies waned as the oil began to flow again. With the beginning of the new millennium, the mood turned once again and environmental, "green" building technologies are now enjoying unprecedented attention from building owners, the general public and design practitioners. Conscious of the past, current high-performance building standards and rating systems including ASHRAE 189.1 and LEED in the US, BREEAM in the UK and CASBEE in Japan, now consider energy efficiency *as well as* building occupant comfort and well-being.[5] Interestingly, a significant contributor to the current popularity of green building rating systems among tenants and building owners alike is the frequently voiced (but little-proven) hypothesis that buildings with a green certification positively affect occupants' health and overall organizational productivity.

Will the current environmental movement lead to more lasting practice models than what its forerunners accomplished during the 1970s? One fundamental difference between now and then is that today's interest in sustainable living is not caused by an immediate shortage of natural resources but rather by growing evidence that man can permanently change the climate of this planet on time scales that span generations rather than millennia. The appearance of ozone holes near the poles, seemingly more frequent environmental disasters and a declining biodiversity constitute for many individuals, young and old, a call for action. In many countries it has become a well-known fact that the building sector alone accounts for some 40% of a country's carbon emissions (Fig 1.3) and governments at all levels are trying to improve energy efficiency in new and existing buildings through stricter legislation and financial incentives. As a consequence of these political forces, the building industry finds

Fig 1.4 Tradeshows such as GreenBuild 2011 in Toronto, Canada, increasingly cater to a mass market

itself in dire need of professionals with expert knowledge of sustainable design techniques and energy-efficient technologies. In a 2010 US survey of 220 A/E/C firms, "sustainability and climate change" were identified as the "biggest emerging concerns" faced by the building industry. In the same survey, deans and department heads of 126 academic architecture programs reported that the most significant changes in their curricula over the previous five years had been related to strengthening their sustainable design course offerings.[6] There is a clear demand for high-quality, up-to-date educational material related to sustainable building design.

Considering existing architectural textbooks there further exists – in the author's opinion – a particular need to expose designers to scientifically grounded workflows to evaluate their ideas rather than having them rely on superficial generalizations such as that "a building has to look South to take full benefit of solar radiation." The stakes are higher than in the past to "get it right." Why? Environmental building design has moved from a smallish group of like-minded individuals to a mainstream movement with considerable financial backing. For example the US Green Building Council's annual GreenBuild conference routinely attracts close to 30,000 visitors. Frankfurt's Light+Building – with 180,000 visitors the world's largest trade fair for lighting and intelligent buildings – picked "energy efficiency" as its main theme in 2012. A growing number of building owners are now willing to step up to the task and request a high-performance "green" building from their design teams. In response, manufacturers and design firms are emphasizing (with varying degrees of rigor) how "green" their product and services are. The recently coined term "green washing" accordingly describes a process in which environmental performance claims for specific products are either misleading or lack solid evidence. In the interest of consumers, the building industry needs more rigorous and reliable evaluation schemes to identify products and design solutions that yield reliable performance.

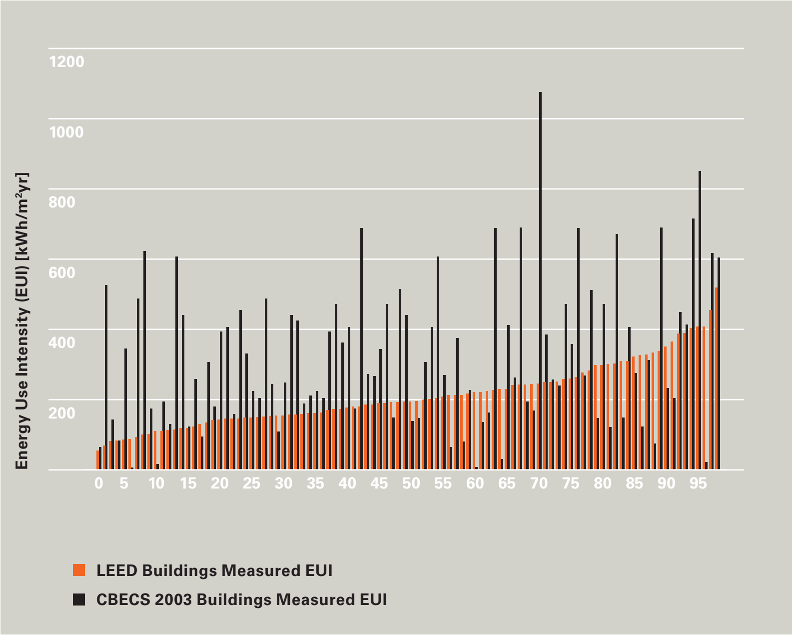

Fig 1.5 Measured Energy Use Intensity of 97 LEED versus matched CBECS buildings

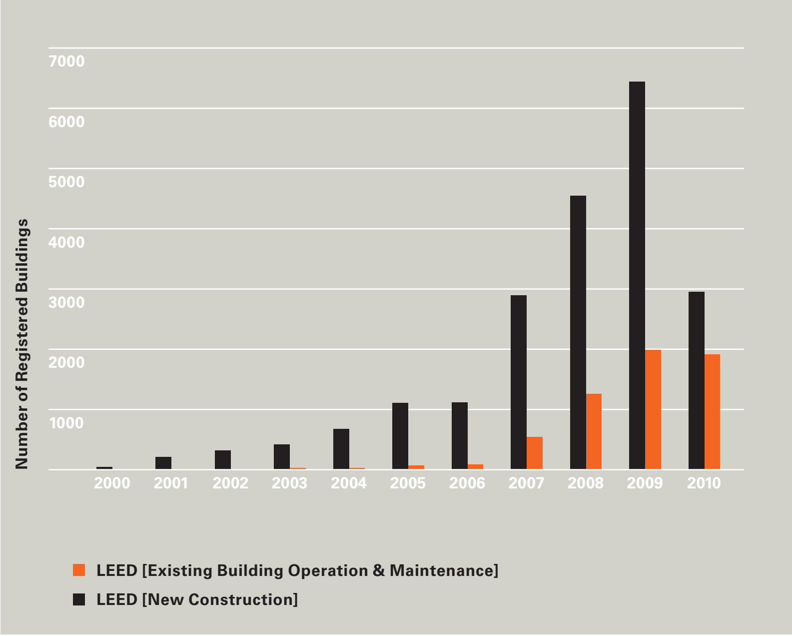

Fig 1.6 Number of LEED buildings certified annually under the categories New Construction as opposed to Existing Buildings: Operations & Maintenance
(Source: USGBC)

Apart from manufacturers, green building rating systems are also under mounting pressure to better meet the expectations of society to deliver more energy-efficient buildings with higher occupancy satisfaction. In the US, the energy performance of the first generation of LEED-certified buildings has been inconsistent. Fig 1.5 shows a comparison of the Energy Use Intensity (EUI) of 97 LEED-certified buildings that were registered before 2006 and their "matched" reference buildings in the 2003 Commercial Buildings Energy Consumption Survey (CBECS) database.[7] EUI corresponds to the energy use of a building divided by its conditioned interior floor area. The matching in Fig 1.5 was conducted based on project size, geographical location and program. While the mean EUI of the 97 LEED buildings was about 30% lower than that of their CBECS counterparts, about a third of the LEED buildings (those "sticking out" in orange in Fig 1.5) actually had *higher* EUIs than their CBECS counterparts. A separate study later pointed out that the larger office buildings in the LEED sample had particularly high EUIs which is why the overall site energy use of the 35 LEED office buildings was statistically equivalent to that of the CBECS office buildings.[8] While it has not been clarified whether some of the high EUIs in the LEED buildings were caused by unexpectedly high building usage rates or actual deficiencies in the buildings, these findings are at least disconcerting for aspiring green building owners. A minimum takeaway from these investigations is that a green building is not a "plug-and-play" product but requires an involved owner who conducts post-occupancy evaluations and is willing to invest in ongoing commissioning. The recent rise of LEED certifications under Existing Buildings: Operations & Maintenance (EBOM) shows that more owners are recognizing this fact (Fig 1.6).

What role does daylighting play within the larger sustainable design discussion? Due to the paired focus on energy efficiency and occupant well-being, daylighting – having stakes in both categories – is a central concern for many projects. Using LEED statistics once more as an indicator of contemporary sustainable design practice, out of over 1200 buildings that were certified under LEED by 2009, 43% and 66% were awarded the *daylighting* and *view* credits, respectively.[9] This number shows that daylighting is a core sustainable design consideration. In contrast, Fig 1.7 compares the indoor environmental satisfaction of occupants in 20 LEED-certified buildings with those in 160 buildings without a "green" rating.[10] While occupants' overall environmental satisfaction as well as satisfaction with thermal comfort and indoor air quality was statistically significantly higher in the LEED buildings, there were no statistically significant differences found for acoustics and lighting. Interestingly, the main occupant complaint for lighting reported in that study was "not enough daylight." This finding suggests that current design analysis techniques for daylighting yield inconsistent results. This book hence proposes a new and enhanced conceptual framework to implement daylight in buildings.

Fig 1.7 Comparison of the occupant satisfaction score for LEED-certified buildings versus the CBE control group

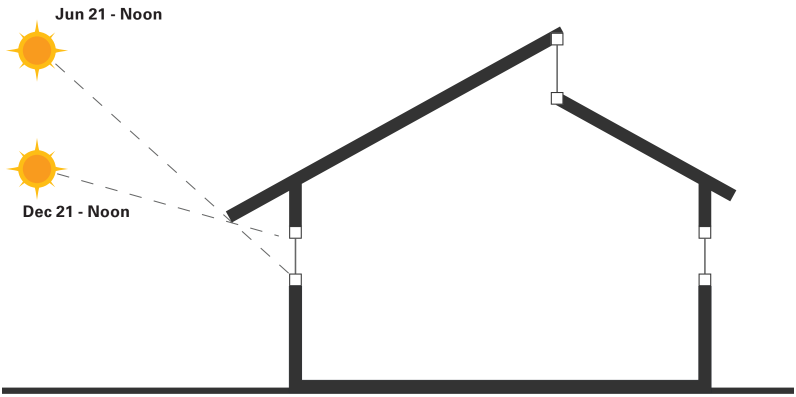

Fig 1.8 Section of a building with sun positions at noon on equinox days

About this Book

The undecided reader browsing through this introduction might concede that yes, daylighting is important, but also remark that the subject is ancient and that there are already several books available on the topic. Is there a need for yet another book and how does this book differ? The author’s motivation for writing the *Daylighting Handbook* came from the observation that – even though there is an increasing variety of mostly computer-based design analysis techniques available for predicting lighting levels and energy use in buildings and while these techniques are accessible to nonexperts – most designers are missing a holistic framework of how to effectively apply them to their particular projects. For example, many architectural students nowadays provide sections or animations of sun positions during noon on solar solstice and equinox days as part of their initial site evaluations and for façade studies (Fig 1.8). But, insight in how to effectively use this information and integrate it into the design of a building is mostly missing.

Several of the design analysis techniques presented in this book are so recent that they have thus far been published only in scientific journals for a very specialized audience. Some were developed while writing this manuscript. The *Daylighting Handbook* aims to interweave old and tested daylighting wisdom with these more recent techniques. At the same time, the book challenges or clarifies existing design workflows if scientific evidence discredits them. The resulting document presents a framework for designing with daylight that encompasses a combination of interrelated rules of thumb, computer simulations and scale model analysis (Fig 1.9). The book aims for a level of detail that allows the reader to understand the assumptions underlying the analysis techniques without being overly cumbersome to read.

The *Daylighting Handbook* intends to describe concepts that are timeless, such as when a building should or should not avoid solar gains depending on program and climate. This information takes some time to digest and is not going to change over time. It is hence more suitably presented as a book rather than a website. In contrast, descriptions of how to derive this type of information using any particular software are constantly changing and hence better disseminated via online tutorials.[11]

The complete *Daylighting Handbook* will consist of two volumes. This first volume is divided into two parts. *Fundamentals* serves as a general introduction to daylighting (chapter 2), its implementation and its daily and seasonal availability (chapter 3). It also explains how light helps us to perceive the world around us and to maintain our circadian rhythm (chapter 4). A first practical approach to building massing via rules of thumb is provided in chapter 5.

Designing with the Sun is comprised of chapters 6 to 8 and introduces the user to methods to determine where the sun is located in the sky with respect to a building site throughout the year (chapter 6). Chapter 7 shows how this information can be used to design static shading devices. Heliodon studies using physical models are discussed in chapter 8. Most chapters finish with suggested activities that the reader is encouraged to work through in order to fully engage with the subject matter.

The focus audience for the *Daylighting Handbook* consists of practicing architects and consultants as well as of architectural students who are learning about daylighting and sustainable design for the first time. The book should ideally be consumed from beginning to end as many of the design analysis techniques build upon each other. Alternatively, the reader should go through chapter 2 to 4 and then use the table of contents and chapter summaries to jump back and forth throughout the text. The complete *Daylighting Handbook* series will lend itself to be used as a textbook for a semester-long university-level course.[12]

The DIVA Approach

The book promotes an evidence-based approach towards building design which we internally refer to as the "DIVA" approach. DIVA stands for design, iterate, validate and adapt. DIVA's underlying premise is that an informed design decision is a better design decision and that a series of "better"

Design Stage	Analysis Method	Chapter
Schematic design	Use rules of thumb to explore various massing strategies in order to ensure sufficient access to diffuse daylight.	5
	Use direct shading studies combined with simple heat balance models to control direct sunlight.	6–7
	Use radiation maps to evaluate active and passive heating strategies.	II-9
	Use urban simulation models to refine your massing and façade opening strategy.	II-10
Design development	Use heliodon studies to better understand the quality and patterns of direct sunlight within and around buildings and to test the appearance of nonstandard materials.	8
	Use integrated daylight availability, visual comfort and energy models to refine your façade design and interior space layout.	II-11–15
	Design an electric lighting control concept that complements the daylight.	II-16
	Test different material finishes and furniture layouts to further enhance occupant comfort.	II-17

Fig 1.9 Framework for designing with daylight

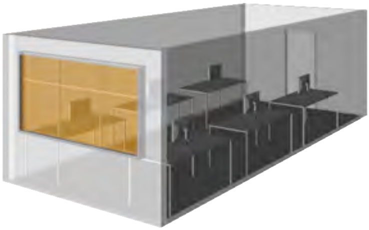

Fig 1.10 Perspective view of the reference office

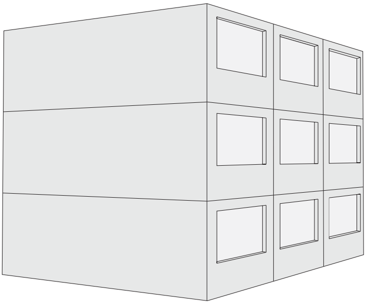

Fig 1.11 Stacked reference offices

decisions will lead to a higher performing overall design. The DIVA approach consists of the following four steps. Initially, the designer formulates a list of project goals, ideally in the form of verifiable performance requirements. Once these goals have been established, the design team should secondly go through a series of design iterations to explore different ideas. The design iterations should thirdly then be evaluated and validated based on the earlier established performance metrics and, finally, future iterations should be adapted so that the initial goals are met by the final design. It is important to stress that the DIVA approach should not be limiting or restrictive for design, but rather encourage consistent thinking. While the book discusses a series of evaluation criteria and performance metrics related to daylight, the choice of which metrics to use should always remain with the design team. Designers are actually encouraged to reassess *and* document their aspirations for each project anew (chapter 2). The clearer these ambitions are formulated at the beginning, the higher the probability that they are met by the final design.

The Reference Office

As discussed in chapter 2, daylighting encompasses multiple, sometimes conflicting, performance dimensions that range from occupant well-being to energy efficiency. It is hence difficult for a designer to develop an intuition about how significant the effect of design parameters such as façade orientation or window height is on the overall daylighting performance of a space. For example, enlarging the size of a window admits more daylight into an adjacent space but may also lead to increased thermal loads. How can a designer weigh these opposing effects against each other? In order to help the reader develop a quantitative intuition for such trade-offs, a sidelit space called the *reference office* is used throughout the book.[13] The reference office is a “typical” south-facing office in Boston. A perspective view of the reference office is shown in Fig 1.10. The reader should think of the reference office as one of many identical rooms stacked together to form a façade (Fig 1.11). Details on the reference office can be found in the Appendix. A summary view of different performance metrics for the reference office – also called a "dashboard view" – is introduced in chapter 2.

Standards and Green Building Rating Systems
Daylighting has long been part of construction standards and green building rating systems. In the UK, the *right to light* of a window can be traced back to the Prescription Act of 1832 and even earlier.[14] The daylighting criteria or metrics used by current and past standards are discussed in this book along with emerging new metrics. Not surprisingly, the reader will discover significant differences between the level of analysis that is technically *possible* as opposed to what standards currently *require* building design teams to carry out. But, affordable computing power, greatly improved CAD design environments and low-cost sensors have become great equalizers between the two-person design firm and the multi-national corporate office. Most of the concepts presented in the *Daylighting Handbook* were hence developed for widespread use by "everybody." In fact it is often in smaller firms, where the decision maker and the person who conducts a performance analysis are the same, that these techniques can be more successfully woven into a holistic design approach. The author therefore anticipates that over time, some of the concepts presented here will become more common practice as more design teams learn about them and software developers provide even better tools to integrate them into the design workflow.

Summary

There is a renewed interest in energy efficiency in buildings combined with improved indoor environmental quality. Daylighting connects both of these design aspects and thus forms a key component in contemporary sustainable design practice. This volume consists of two parts. *Fundamentals* serves as a general introduction to daylighting, occupant needs and sustainable design practice. *Designing with the Sun* introduces methods to determine where the sun is located in the sky, how this information can be used to design static shading devices and how the use of physical scale models can further advance a design. The overall book is based on the DIVA (design, iterate, validate and adapt) approach which promotes an evidence-based attitude towards design.

Suggested Activity – Defining Goals

We all experience light and daylight every day of our life and our attitude towards light, shadows and colors is a direct consequence of how we see the world. As a result, we carry our personal, preconceived notions within us of what constitutes "good lighting" or a "well-daylit space." These intuitions can inform our designs in unique ways. In order to preserve these raw attitudes towards lighting before they become "diluted" by the concepts presented in this book, the reader is encouraged to write a short statement on his or her personal characteristics of a well daylit space as well as any motives for implementing daylight in a project. Photo(s) of daylit space(s) can be very useful to support such thoughts. Going forward, the statement can serve as a personal touchstone.

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