LBL-13305
EEB-W-81-19

Presented at the Sixth National Passive Solar Conference, Portland OR, September 8-12, 1981.

THE USE OF PHYSICAL SCALE MODELS FOR DAYLIGHTING ANALYSIS

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SEPTEMBER 1981

The work described in this paper was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

This work was conducted as part of the Lawrence Berkeley Laboratory's Windows and Daylighting Program with support provided by the U.S. Department of Energy. For further information regarding related program activities, please contact:

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ABSTRACT

A process is described for determining the quantitative and qualitative features of a proposed daylighting design using physical scale models. The paper presents and discusses in detail several issues (i.e., modeling techniques, testing, measurement, visual analysis and photography) that must be resolved before physical scale modeling can be undertaken. Finally, a physical scale modeling case study is presented which illustrates many of the issues outlined as well as a photographic sequence of the physical scale modeling process.

1. INTRODUCTION

Daylighting is now considered one of the most promising energy conservation strategies for nonresidential buildings. Although substantial savings in both electical energy and peak power demand are possible, potential savings may not be achieved unless daylighting design tools are agreed upon.

Three types of design tools have been used to predict interior daylight illumination: physical scale models, graphic techniques, and calculations. The daylighting design tool development activities of the Lawrence Berkeley Laboratory's Windows and Daylighting Program[1] have done much to standardize daylighting evaluation tools within the latter two categories. However, there still exist many misconceptions about how to effectively use physical scale models for daylighting design and analysis. This paper will attempt to dispel many of these misconceptions by presenting some of our recent physical scale modeling experiences.

It has been known for some time that the physical scale model is the most reliable daylighting evaluation tool available.[2] The physics of light is such that a physical scale model which duplicates a full scale space in all respects and tested under the same sky will yield identical results. Although it is not always possible to exactly duplicate a full scale space during the design process when so many issues are changing, the advantages of using physical scale models significantly outweigh their disadvantages. Some of these advantages are as follows. First, physical scale models, even very crude ones can provide accurate performance information when single-element design comparisons are to be made. Secondly, physical scale model building is a common practice among many architectural offices and with slight modifications, can result in a sensitive design tool for daylighting analysis in addition to continuing to be an effective communication device. Thirdly, physical scale models offer an opportunity for qualitative evaluation through either visual observation or photography.

2. MODELING TECHNIQUES

Physical scale models can be constructed quite easily from a variety of materials such as plywood, cardboard or formboard; however care should be taken to insure that these materials are opaque. The amount of detail to be included in the model depends upon the use to which the model is put. Models for quantitative studies do not require a considerable amount of detailing whereas models for qualitative studies do. However, both modeling uses are particularly sensitive to the reflectivity of internal surfaces. For quantitative studies, surfaces may be finished with grey paper or paint which approximates the appropriate surface reflectances, whereas qualitative studies require the use of color paper or paint which duplicates the surface color. Room surfaces that have a spectral character should be modeled as closely as possible, especially if qualitative studies are proposed. Care must be taken to accurately detail all light openings as well as maintain the geometric relationships between the model and the overall size of these openings. Window glass can be duplicated by the use of either the proposed glazing material or an acrylic plastic sheet with the same transmission as the proposed glass. Other detailing will depend upon the design stage in which the modeling activity is undertaken, the building type which is to be modeled and the skill of the model maker.

Physical scale modeling usually requires a high degree of flexibility, which tends to suggest that a "modular-type" of construction be used in which the model base becomes a support structure into which various window, wall, and ceiling configurations can be "plugged" in for testing. This high degree of flexibility allows for easy manipulation of single-element design comparisons.

In theory, the scale at which a model is to be built is of no significance. However, there are a number of practical considerations that tend to suggest an appropriate scale. In quantitative studies the relative size of the photo-sensor probe may cause a photometric disturbance when inserted into a small scale model.[3] In addition, illumination measurements are usually taken at desk height (30 inches above the floor) which makes the photo-sensor probe's height critical in scale determination. It has been our experience that in general a scale of 1 inch to 1 foot be used for small interiors with ceiling heights of 10 feet, and a scale of 1/2 inch to 1 foot for larger interior spaces. In qualitative studies, an approximate doubling of these scales is needed in order to provide a realistic field of view for visual observation and a proper depth of field for photographic documentation. Other factors such as convenience of construction and transport should not be overlooked when one is considering scale.

3. TESTING

Physical scale model testing may be conducted in an artificial sky or under actual sky conditions. The artificial sky simulates a fixed sky condition (usually uniform or overcast) which remains constant in order that design alternatives can be identically compared. There are two basic types of artificial sky, the hemispherical and the rectilinear sky. The hemispherical sky takes the form of a dome with an interior white reflecting surface illuminated by banks of lamps around its base. The rectilinear sky takes the form of a large rectilinear box inside which is a luminous ceiling plane surrounded by vertical mirrors on its four sides. The use of one of these skies is extremely advantageous for daylighting analysis, unfortunately there are only about a half dozen of these skies presently in use in the U.S., making access to such a facility quite difficult.

Testing under an actual sky is the cheapest and easiest test to perform. However, it is with this method that the greatest chance of errors exists. These errors are often caused by the changing character of the sky going uncorrected during the testing process. This problem can be easily overcome by taking daylighting measurement in relative (a ratio of interior to exterior illumination) rather than in absolute terms (interior illumination only). Such an approach tends to correct varying sky conditions and has been used in the daylighting field for some time. The "daylight factor" (ratio of interior illumination to horizontal sky illumination) and "window factor" (ratio of interior illumination to vertical illumination striking the outside of the window) are two relative measures which should be used in testing. The daylight factor is more appropriate for testing under overcast sky conditions whereas the window factor is more appropriate for testing under clear sky conditions, especially if direct sunlight is present.

It is frequently necessary to test the performance of various daylighting considerations at several times throughout the year without having to wait for these times to arrive. A sundial box[4] and a model stand which can be pivoted both horizontally and vertically is very useful for this purpose. However care must be taken when tilting the model to the appropriate solar altitude because the model may be seeing a greater portion of the ground plane. This problem becomes critical when one is attempting to model a mid-day summer solar position on a winter day. The opposite situation (modeling a winter solar position on a summer day) poses no such problem because the low morning and evening solar altitudes simulate winter conditions quite well. Care should be taken when model testing outdoors as to local obstructions such as trees and buildings which can substantially alter test results. Any obstructions that need to be modeled need only be accurate as far as scale and reflectivity is concerned. The most ideal situation is to take the model to the actual site for testing.

4. MEASUREMENT

The most important as well as the most expensive aspect of physical scale modeling is the need for an accurate measureing device. Such devices are called photometers (light meters) which are similar to a photocell. However, unlike a photocell, the photometer is usually color corrected (having a "viscor filter"), which makes it sensitive only to the visible portions of the solar spectrum. In addition, the photometer should also be cosine corrected, so that the photo-sensor response is in accordance with the cosine law of illumination.

For daylighting measurement, the photometer should range from 1 to 10,000 footcandles. When a photometer does not have such a range, it is often possible to extend its range by covering the photo-sensor with a filter or perforated cap which allows a certain percent of incident light to penetrate. The inverse of this percentage becomes the factor by which the photometer reading is multiplied to attain the proper illumination (e.g., a 10% transmitting filter means that the photometer scale is factored by x10). Photometers which have the photo-sensor and display in the same case are not well suited for model studies since they tend to cause the observer to block incident light when reading takes place. This problem makes photometers with photo-sensors that are remote (on a wire) from the display much more desirable. Photometers which have the ability to "grow" (add photo-sensors) greatly facilate measurement taking, since numerous reference points as well as relative measurements can be simultaneously recorded. Such devices can cost from $200 to $1500 depending on the options and accuracy required.

Positioning of the photo-sensor(s) within the model can be aided by the use of a reference grid, which assures proper location for comparative measurements. We have found the 3 by 3 grid (9 reference points) to be the most convenient for standard rooms. A number of small access holes that correspond to one side of the proposed grid (usually 3 holes) should be made in the wall panel opposite the window-wall. The photo-sensor is attached to one end of a stick which can be moved back and forth through these holes to each of the reference points on that line. Marks along the stick (usually 3) can be used to line up each reference point. Care should be taken to guard against unwanted light penetrating the access holes.

5. VISUAL ANALYSIS

There are many aspects of daylighting which do not lend themselves to quantitative measurement.[2] Such issues as glare, contrast and visual comfort can only be studied by direct visual observations, which may or may not be accompanied by quantitative analysis. Qualitative analysis generally requires greater realism (i.e., furniture, carpeting, texture and reflectivity of surfaces) than does quantitative analysis. In addition qualitative models require viewports at eye level, which should correspond to the predominate views within the space. We have found that for visual analysis the viewports should be perpendicular to the window-wall for the best results. Care should be taken to guard against unwanted light penetrating the viewports.

5.1 Photographic Analysis

Photographic analysis is similar to direct visual observation; when differences occur they are due to photographic limitations. The human eye is much more sensitive than even the most sensitive of films. Thus, even under the best of circumstances photographs tend to distort the actual luminious condition as seen by the eye. This problem can be overcome by bracketing each photographic shot (i.e., shooting at the exposure as well as one exposure above and below); the photograph that most correctly corresponds to the qualities found via direct visual observation is selected for use. Such an approach requires considerable documentation; this can be provided by a small display panel (which documents sky condition, relative azimuth, solar altitude and exterior illumination with moveable pins) which can be photographed within the model.

A single lens reflex (SLR) camera with thru-the-lens viewfinder is the most appropriate for photographic analysis. Wide angle lenses (e.g., 21, 24 and 28MM) provide the most realistic view of the space. Fast film such as ASA 400 daylight allows the smallest aperture (F16 - F22) for the greatest depth-of-field. Care should be taken in choosing the types of film because some are color biased (sensitive to a narrow range of color) and may not accurately portray the colors of the space.

Photographic analysis requires circular lensports the diameter of the camera lens and should be positioned at eye level. We have found that for photographic analysis the lensports should be perpendicular to the window-wall for the best results. Care should be taken to confirm that the camera lens is snug to the lensport, so that unwanted light can not penetrate.

6. CASE STUDY

A small commercial office space was selected for our modeling exercise. Information concerning this space (i.e., color, texture and reflectivity of all interior surfaces) was documented on several trips to the actual site. A model base and support structure were then prepared at a scale of 1 inch to 1 foot to receive various window, wall and ceiling configurations. All wall panels were constructed in duplicate to provide access for both the photometer and the camera. The glazing used in the actual space was duplicated and used in the initial comparisons. Furniture was then modeled and doll house accessories (i.e., books, magazines and telephones) were purchased for added realism. For this particular model, the artificial lighting system was also modeled using small neon tubes, mylar reflectors, and translucent covered cutouts in the ceiling panel to simulate the luminaires. The entire lighting system was connected to a dimmer for energy modeling purposes.

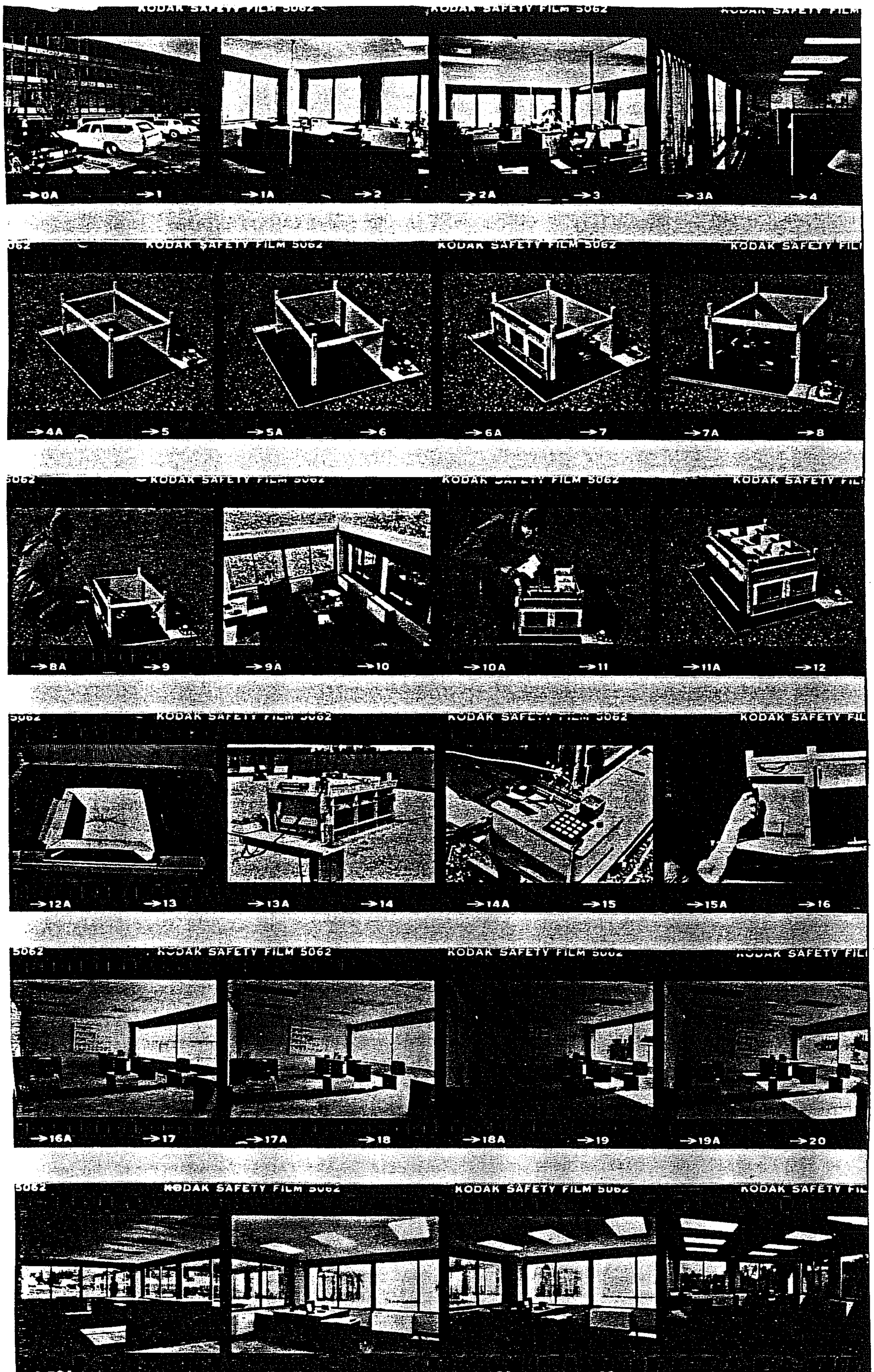

Fig. 1. Modeling Sequence (row 1 existing space; rows 2 and 3 model construction; row 4 instrumentation and photography; row 5 measurement; row 6 qualitative assessment)

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Photometric measurement for this model included several photo-sensors connected to a datalogger, which allows multiple reference points to be simultaneously recorded. The model was transported to the site on several occasions so that comparisons to the actual office space could be made. In addition to quantitative analysis, numerous direct visual observations as well as photographic analysis were performed. Figure 1 is a photographic sequence which illustrates the case study process.

7. CONCLUSION

A physical scale modeling process for daylighting design has been presented which can (1) provide accurate performance information, (2) link itself with existing model building practices, and (3) provide an opportunity for qualitative evaluation. It is hoped that the application of physical scale modeling will encourage the use of daylighting, as well as place daylighting in a proper relationship to other design considerations. For more information on the availability of physical scale modeling techniques and other daylighting design tools, write to: Windows and Daylighting Program, Lawrence Berkeley Laboratory, Building 90, Room 3111, Berkeley, California 94720.

8. ACKNOWLEDGEMENT

The work described in this paper was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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