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A Guide for Building Daylight Scale Models

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Abstract: Scale models are used frequently to evaluate the daylighting performance of buildings. In order to get accurate results, there are several rules to respect when building these scale models. Some of these rules are universal, while others depend on the measurement and observation devices, the type of sky under which the study is carried out, and the objectives of the study. This paper, based on the author's experience and on a literature review, presents rules to respect when building a mock-up for daylighting studies. These rules are illustrated by project examples that were tested under the Belgian artificial skies (single-patch sky and sun simulator, mirror box and mechanical sun).

Keywords: Daylighting, Scale models, Artificial sky

Introduction and Organisation

Daylighting is one of the key elements of all architecture projects. Architects have used scale models for centuries in order to evaluate their projects under a real sky. Moreover, the development of artificial skies and suns has made these studies less dependent on factors such as the weather, the time or the date (Kittler, 1959). When properly constructed, scale models portray the distribution of daylight within the model exactly as in a full-size room. Comparison studies of simple models have shown that daylighting studies carried out under sky and sun simulators can give very accurate results (Bodart, Deneyer, De Herde & Wouters, 2005). However, models that are more complex will generate modelling errors if the models are not built accurately and with respect to several rules.

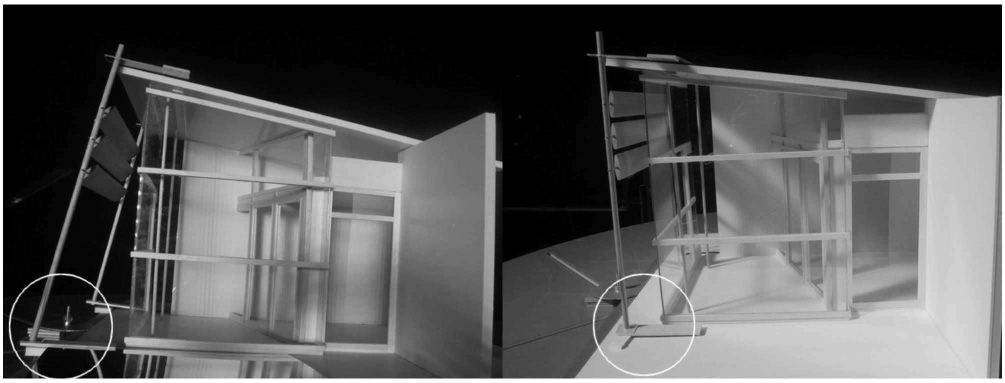

Figure 1: *Example of modularity of a solar shading system.*

This paper describes these rules in detail and gives some advice for the building of architectural scale models in order to achieve precise daylighting measurements and analyses. The next section lists information that is essential for the laboratory technician and the following one encourages the model designer to use modular models that are always less expensive than using different models. The next section shows that the scale of the model should be chosen as a function of the study's objectives but also as a function of the type of sky and the measuring devices used for the study. This is followed by a section showing that inaccuracy in the model geometry can lead to large errors. The next section discusses the illuminance sensor and the camera position while some advice on the joining of edges is given in afterwards. This is followed by a discussion of the scale model material colour and reflection mode; a link is made to a web tool especially focussed on this aspect. The window geometry and material is discussed. Finally, the last two sections introduce the modelling of external surfaces.

Figure 2: *Mass model (scale 1/200).*

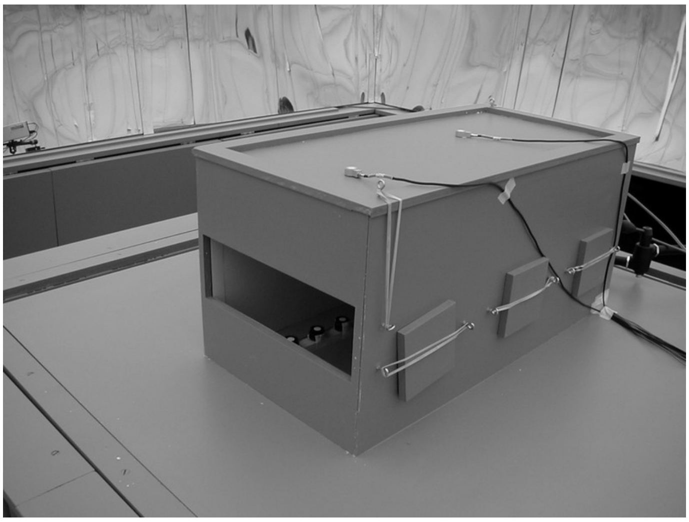

Figure 3: *Model for a detailed study of the daylighting penetration (scale 1/10).*

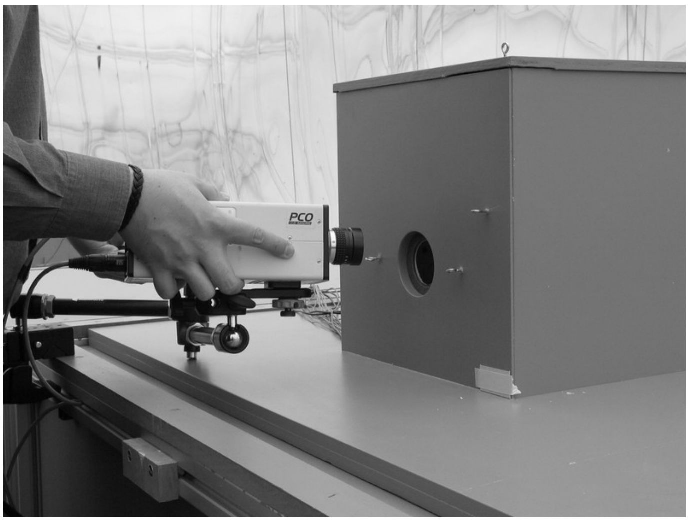

Figure 4: *Opening for a camera.*

General information such as precise building or site orientation, site latitude, scale of the physical model and name of the building must be clearly referenced on the model. The names of the model designer, the architect and the experimenter should always be clearly noted. In addition, a generic description of the model and the number of elements should be reported. Lastly, a description of the study order and the planned analysis should be included. All of this information should be summarised and reported on an identification card.

Model Modularity

It is simple to test façade or skylight options with one generic model. Different façade configurations can be tested using the same model by modifying only small elements with interchangeable parts. Interchangeable elements should be clearly labelled and an outline of the permutations should be prepared before the tests. A method of easily attaching and removing elements from the model should be planned, For example, the testing of several positions of a solar shading system is possible through the use of an hook and loop tape (Figure 1).

Scale and Size of Models as a Function of Objectives

The construction of a model must be preceded by the determination of the appropriate scale, which is directly related to the model's particular purpose. Scales ranging from 1:500 to 1:1 are to be considered. Three types of scale models may be distinguished in terms of design and performance function (Baker, Fanchiotti & Steemers, 1993; Cannon-Brookes, 1997; International Energy Agency, 2000):

- Massing models for the study of solar access. These are use for site planning as well as building location and orientation exments (see Figure 2).

- Models for studying the building's performance. This includes the investigation of daylight penetration and internal distribu tion, measurement of illuminance and luminance levels, as well as glare and contrast studies (see Figure 3).

- Models for investigating individual apertures, glazings, shading devices or advanced daylighting systems.

Table 1 summarises the possible scale choices as a function of the study's purpose.

The accuracy level of model details must be sufficient to produce the information that is desired. This influences the choice of model size.

Massing models can be built crudely (i.e., the openings do not necessarily have to be modelled) as the objective is to get a general view of the impact of the building's size and location on existing buildings (shadows of one building on another, views, etc.). Full-scale mock-ups used to examine the effectiveness and workability of control elements or new materials must be built with a high degree of accuracy.

Scale and Size of Models as a Function of Artificial Sky or Sun Conditions

The scale model size can also be fixed by the visualisation type or by the measurement devices used in the model. When testing under an artificial sky or sun, restriction on the size can also come from the artificial sky or sun. Under artificial sky simulators, the parallax error increases as the scale model size increases. Maximal size dimensions have to be fixed for each artificial sky, according to its dimensions. In order to limit the parallax error due to the finite dimensions of the sky vault, the maximal dimensions of scale models are generally set to a maximum of 10 % of the apparent diameter of the sky vault. The one patch sky simulator of the Belgian Building Research Institute has an apparent diameter of 13.8 m; therefore, the models size is limited to 1.1m x 1.1 m x 0.7 m (Bodart, Deneyer, De Herde & Wouters, 2006).

For shading analysis under a sun simulator, the size of the model must be reasonable with regard to the distance to the light source and the width of the sun spot.

Scale and Size of Models as a Function of the Characteristics of the Measurement Device

For internal pictures, it is essential to focus on at least one room surface. Usually, a macro lens with a focal distance lower than 28 mm is used. It allows a sharp image at low distance and has a large opening angle. This leads to a floor to ceiling minimal height of 0.15 metre and a minimal room depth of about 0.30 metres. For most of the buildings, this corresponds to a minimal scale of about 1/20 to 1/25.

Figure 4 shows an example of the placement of the camera in a model. In order to obtain a view comparable to the view that would be obtained in the real room, it is necessary to place the lens centre at the eye's height, in the scale model. This height varies between 1.5 and 1.7 metre. For a scale of 1/20, this corresponds to 75 or 85 mm height in the scale model. Depending on the lens diameter, a scale higher than 1/20 can be required.

The illuminance sensor size can also influence the scale, since the illuminance should be measured at work plane height. With sensors of 15 mm height, the minimum scale for modelling a working plane of 0.8 m height is 1/20.

Model dimensions are also limited by practicality factors specific to the testing location. For example, the laboratory door's width, the turntable dimension, the fixation system or even the model transportation mode may provide model size constraints.

Model Geometry and the Modelling of Walls

Accurate model geometry and material selection are quite important when attempting to mimic the conditions of a full-scale building. Inaccurate on-site measurements can cause substantial errors on the light quantity and distribution in the scale model (Cannon-Brookes, 1997). Thanachareonkit, Scartezzini and Andersen (2005) found that the key factors influencing the discrepancies between the scale model and the real building are the accuracy of geometric dimensions and the internal surface reflectances.

Each surface must be modelled carefully. Mirrors are useful for the modelling of large symmetrical spaces but only under overcast sky analysis. Under clear sky conditions, the direct sun reflects off the mirror into the space, creating light distribution errors. Mirrors must be fixed very accurately and taped with black tape. Horizontal and vertical surfaces must thus be perfectly aligned to avoid any light penetration that would be reflected by the mirror and create large sources of error. Figure 5 shows outside and inside views of a scale model built with two mirrors in order to model a very long space.

Internal walls have a large influence on light penetration and distribution. It is thus essential to model them correctly. Furniture can also influence the light distribution; its influence depends on colour, size and location. However, furniture modelling can be time-consuming and increase the model budget. Though it is not compulsory for preliminary studies, it is interesting to model the furniture in the final phase of the project in order to visualise the final design solution. Figure 6 showing a meeting room (left) and

Table 1: Scale choice as a function of daylighting design purpose (International Energy Agency 2000).

Scale	Objectives
1/200 to 1/500	For preliminary design and concept development To provide a gross sense of the massing of the project To study the shadows generated by the future building or from a neighbouring building
1/200 to 1/50	To study direct sunlight penetration into a building To study diffuse daylight in a very big space
1/100 to 1/10	To consider detailed refinement of spatial components To have highly detailed inside views To study accurately diffuse and direct daylight penetration
1/10 to 1/1	To integrate critical industrial components To consider daylighting devices that cannot be reduced in scale To proceed to final evaluation of advanced daylighting systems through monitoring and user assessment

a swimming pool (right) shows that pictures taken in mock-ups can be very realistic.

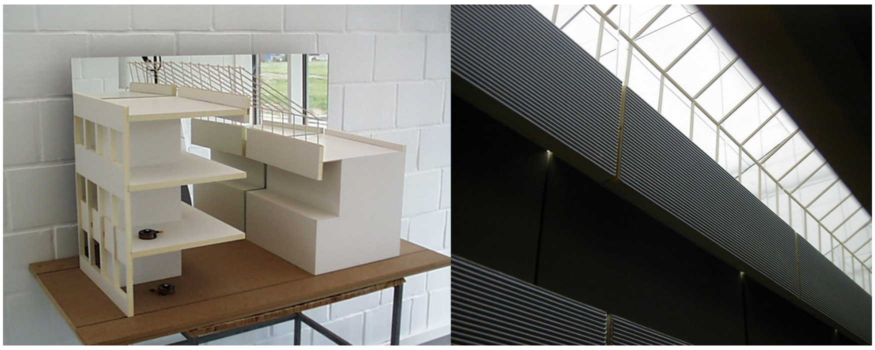

Figure 5: *Example of mirror use for the modelling of symmetrical spaces (one mirror has been removed for taking the left picture).*

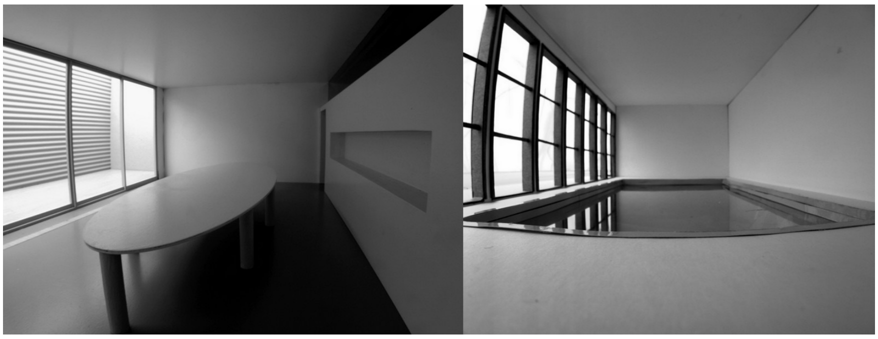

Figure 6*: Pictures taken in a mock-up model (meeting room and swimming pool).*

Sensor and Camera Location

Access to the interior of a model is necessary in order to place the illuminance sensors. If there is no opening such as a window near the measurement points that allows the sensor to be placed, then one of the external walls must be easily removable. It can also be useful to plan a small hole used for the passage of sensor wires through an external wall (Figure 7).

It is essential that the sensor wires do not pass through a wall that needs to be moved during the measurements in order to avoid displacing the sensors during the study. This is time consuming and can lead to problems of accuracy in the positioning of the sensors.

It is essential to mark and number the measurement points before the measurement phase. An interesting solution to this issue is to cover the floor with a printed grid that can be marked at the edges with numbers in one direction and letters in the other (Seattle Daylighting Lab, 2006).

For vertical illuminance measurements, holes must be made in the walls in order to align the top of the sensor with the wall plane. For qualitative analysis, these holes could later be covered with miniature art works in the case of a museum, for example.

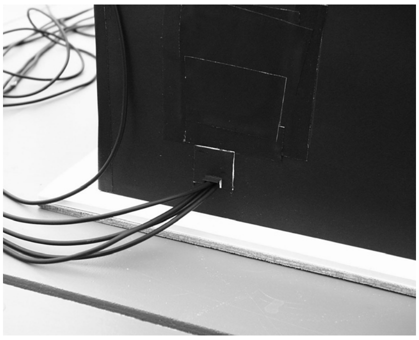

Figure 7. *Example of an opening for sensor wires.*

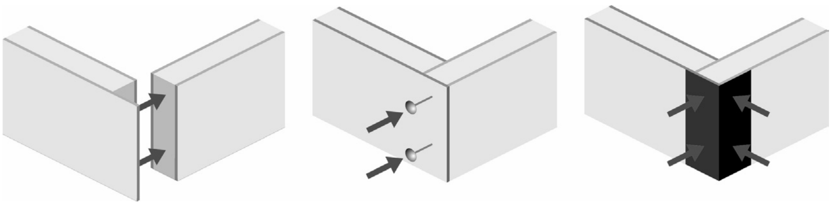

Figure 8: *Fixation of moveable foam-core walls [after Baker & Steemers (2002)].*

Figure 9: *Foam core should be covered with non translucent dark paper.*

Effective camera view ports must be provided. They should be easily accessible and large enough to allow the best camera orientation in order to create the most interesting views. Each view port should be labelled and covers must be constructed to seal these holes when they are not in use.

Edge Joining and Material Selection

All light leaks must be avoided. Light leaks are a key source of inaccuracy, especially in poorly daylit rooms. For scale models made of foam core, joints can be made following the technique shown in Figure 8 and covered by black tape.

When building scale models for daylighting analysis, almost every material that is usually

Figure 10: *Mock-up of an atrium.*

used for architectural models can be used. However, material properties relating to light should be as close to those of real building materials as possible, even though this is not always important for a conceptual model. For example, white foam core, which is often used for the building of scale models, is translucent. It is thus necessary to cover the foam core with non translucent dark paper (see Figure 9). If white foam core or another translucent building material is used, it is easiest is to stick black paper to a large sheet of the material before beginning the model construction. Black foam core is also available, which offers a convenient solution to this problem.

Wood can also be used for mock-up building. This results in very robust mock-ups but the disadvantage is that their weight grows rapidly.

Colour and Wall Reflectance

Material choice is dependent on the study's purpose. For an accurate quantitative luminance and illuminance study, it is essential to choose scale model materials with reflectance and lightness very close to those of the full scale building's materials.

An overvaluation of the reflectance can lead to large errors. For example, if a vertical wall has a reflectance of 50 % and the scale model has white walls of 85 % reflectance, the measurements made in the scale model can over predict the results by about 150 to 200 % for a point located at the far end of the room.

For a black and white visualisation in a scale model, the wall lightness is most important, while for a quantitative daylighting study, it is preferable to select a material with a reflectance very close to that of the full-scale material.

If the objective of the study is to evaluate the visual impression felt in the room, the colour of the scale model materials should be as close as possible to those of the full-scale material.

White foam core is shinier than most real internal wall materials; it should always be covered by diffusing paper, on its inside side, unless the real material is shiny.

As the choice of the best scale model material is difficult, the authors propose the use of a web tool they developed to assist the scale model designer (Bodart, de Peñaranda & Gilbert, 2006). This web tool proposes a large variety of scale model materials most accurately to represent the colour, the lightness, the reflectance and the reflection properties of the real material.

Modelling of Openings

Windows must be modelled accurately as they affect the internal daylight penetration and distribution; it is important to model the window size correctly as well as details such as the window sill.

If possible, the designer should use a thin piece of glass of 3 to 6 mm in width that has the same optical properties as the real glazing. This may be achieved using glazing with coatings directly delivered by the manufacturers. If there is no glazing available, measurements can be done without any glazing. A reduction factor is then introduced in order to correct the experimental results.

However, if the main source of daylight enters the building at angles of incidence of 60° or greater, the glazing material must be included in the model in order to ascertain the proportion of daylight that reflects off the glazing. Figure 10 shows the scale model of an atrium. Glazing must be included in this case because the light's reflection off the windows significantly influences the quantity of light entering the lower floors rooms.

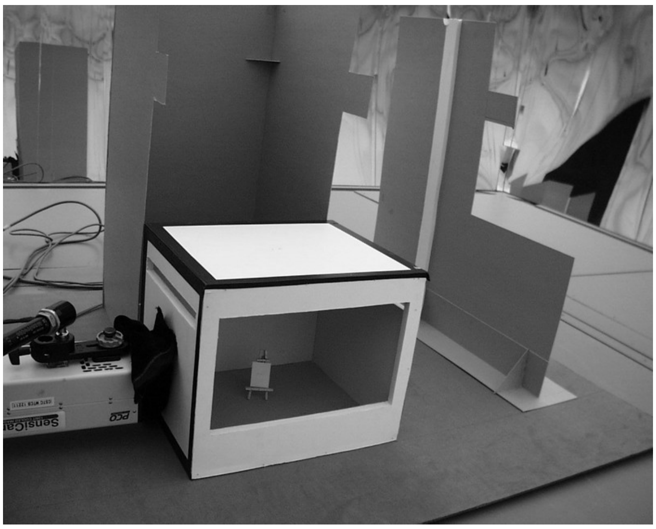

Figure 11: *Modelling of obstructions.*

The opening's size must correspond to the glazed part of the window unless the frame is included and precisely modelled.

Modelling of Outside Ground and External Obstructions

In some cases, the proportion of externally reflected light that enters a room is high. It is thus essential to represent accurately the reflectance and colour of the external ground unless the windows are all roof windows.

The size and the colour of near external obstructions such as neighbour buildings and vegetation must be modelled accurately as shown in Figure 11. However, the reflectance of the external surfaces of the building itself have low influence on the internal light level. Thus, they can be covered with black paper without significantly influencing the internal results.

Conclusions

Building a daylight scale model is no more difficult than building a traditional architectural model usually used to visualise the building geometry and volumes. However, there are some rules that have to be integrated when building a daylighting model in order to obtain results that are as accurate as possible. It is essential to consider these rules before starting the scale model building and integrate them into the building process. Some of the rules are general and others are specific, varying as a function of the daylight laboratory. These general rules include respect for geometry, the elimination of all light leaks, material choice and the inclusion of furniture in models. Specific rules concern, for example, model, illuminance sensor, and camera port dimensions. This paper describes the major rules that must be respected and introduces additional considerations that will help scale model designers to ask good questions of lighting technicians before model building. It is essential to respect each of these rules in order to obtain accurate daylighting scale-model study results.

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