EVALUATING DAYLIGHT PERFORMANCE IN A PASSIVE SOLAR HOME: A STUDY BASED ON DESIGN SIMULATION AND POST-OCCUPANCY MONITORING RESULTS

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ABSTRACT

The following discussion presents the preliminary results of a systematic evaluation of the daylighting design scheme of the Iowa State University's solar home built for the 2009 DOE Solar Decathlon. Illumination levels were recorded for 12 months. Although illumination was not recorded to the levels for which the house was designed for, the occupant records suggest satisfaction with the light conditions in the space. Identifying daylight conditions that are satisfactory to the occupants will help researchers and designers understand what range of illumination is comfortable for daylit solar home occupants. Satisfactory daylight and interior environment conditions will be further identified through a series of proposed surveys taken by the building occupants. Establishing an acceptable range of illumination data will open up research on pairing qualitative and quantitative aspects of solar home design, so that conditions which make the environment a comfortable and functional day lit space can be further studied.

1. BACKGROUND

Passive solar advocates have had a strong impact on contemporary architecture and building practices. Design strategies integrating solar energy have come to be more common and a part of public awareness. This increase in familiarity has also come at a time when computer simulation tools are increasingly available and accessible, and Building Information Modeling is a priority to a number of architecture professionals. With these advances come issues of validity and reliability. By systematically comparing simulations to actual building performance after the completion of construction, the effectiveness of simulation programs can be evaluated. Not only will this allow for the software programmers of these simulation programs to refine the technology, but it will also provide an invaluable collection of qualitative data. By contributing qualitative information to the simulation programs, architects will be able to build with not only energy efficiency in mind, but also comfort, beauty and collaboration.

2. IOWA STATE UNIVERSITY SOLAR DECATHLON HOUSE OVERVIEW

Over the course of three years, an interdisciplinary team of Iowa State students planned and tested the ISU entry to the 2009 US Department of Energy Solar Decathlon competition. The international competition prompted collegiate teams to design and construct an 800 sf home, which is entirely powered by solar energy. The house was aimed towards an aging couple who have downsized from a family home, and are interested in reducing their carbon footprint. With this scenario in mind, the Interlock House was conceived as a comfortable, intuitive, and affordable living space. The house was also developed with the intent of being located in the Iowa climate characterized by cold winters and hot, humid summers.

The interlock scheme was derived from these parameters. The floor plan is arranged around a sunspace that provides many opportunities for reconfiguration based on the climatic conditions. This allows the occupants to manipulate the space, interlocking them from one function to another. These interactions are all made possible by a series of operable glass walls and the sunspace can thus be opened, closed, or partially adjusted.

During the daytime, the Interlock House is entirely lit by daylight. This is made possible by multi-tiered daylighting strategy comprised of northern clerestory windows, southern fenestration, a sunspace, and an interlocking floor plan (Fig. 1). The angled roof and north clerestory windows wash the space with ambient light, while direct light is provided through southern openings that are diffused by window louvers. This layered lighting scheme not only provides the occupants with consistent daylight throughout the day, but also reduces glare, which is a common issue as people age. The distribution of light provides the older occupants with a safe and energy efficient environment, and also animates the space, making it appear larger and brighter despite the 800 square feet (ca. 80 square meters) building footprint.

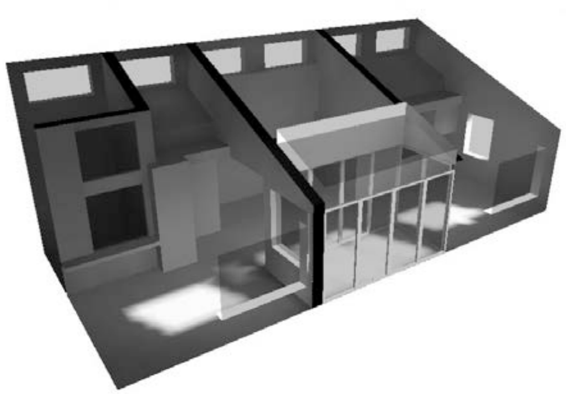

Fig. 1: Interlock House Rendering (ISU Team)

2.1 Current Occupancy

After the completion of the 2009 Solar Decathlon competition, the Iowa Department of Natural Resources agreed to take on the Interlock House as an office space for two of their employees. The house is now permanently situated at the edge of the main campus at Honey Creek Resort in Moravia, Iowa (Figure 2). The Interlock House functions as a nature preserve, where resort visitors come to learn about the local plants, animals, and activities offered at the resort. As a result of this programmatic shift from the original design scheme, the house is only occupied during normal daytime office hours of roughly 8 AM to 5 PM and sometimes into the night with night time activities. Along with its two human occupants, the house also hosts a range of plants and small animals that place various unplanned demands on the interior environmental conditions.

Fig. 2: Interlock House Interior

With the change in program from home to office came a shift in the expectations of building performance. Originally the house would have needed to function most comfortably in the morning, evening, and nighttime hours when the occupants were home from work, except for weekends. The current occupant pattern expects the house to function in opposition to its design intent, with optimal comfort conditions being during daytime hours. This adjustment to full daytime occupation has provided Iowa State University researchers with the opportunity to study the daytime illumination with the contribution of anecdotal occupant feedback about specific aspects of the lighting scheme under a variety of conditions.

After occupants moved into the solar home, researchers began to notice how rarely they relied on the artificial lighting to illuminate work surfaces during daytime hours. On a sunny or partly cloudy day, the occupants rarely have to make any adjustments to the house to regularly function and perform their work, with the exception of cloudy or stormy days. This reliance on daylight is shown in Fig. 3 and Fig. 4, which display the relationship between outdoor radiation, interior illumination readings, and energy consumption used by artificial lights. Light level readings at the solar home are often below the illumination levels for which the house was designed for, yet occupants do not display any type of dissatisfaction. This research will identify normal house performance patterns, as well as occasions when irregular performance is recorded. A series of survey questions will then be proposed, which will seek to pair the quantitative performance measurements with qualitative feedback from the occupants. Ultimately, the research would like to know how comfortable the occupants are in the solar home, what aspects make them uncomfortable, and when these occur.

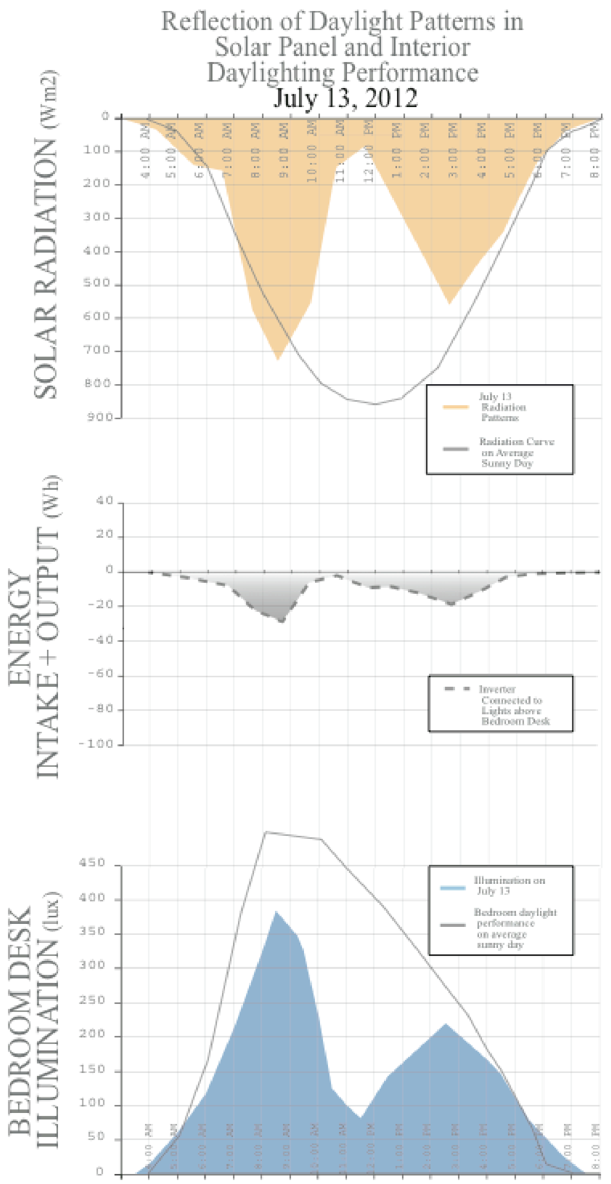

Fig. 3: Radiation, electricity use, and daylight patterns for bedroom desk on typical cloudy day

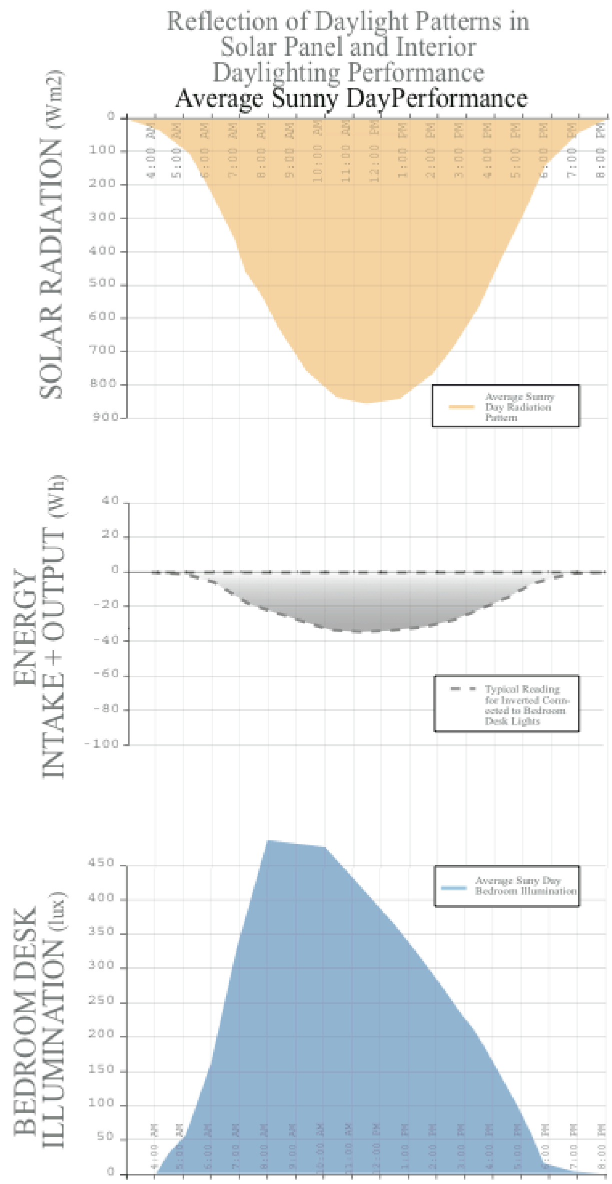

Fig. 4: Average radiation, electricity use, and daylight patterns for bedroom desk on a sunny day

3. METHODOLOGY

The general goal of this study is to identify normal patterns in daylight performance in order to lay the groundwork for understanding what qualitative aspects of solar home occupation can be matched with quantitative light and energy measurements. After average performance is established, the daylight is compared to the pre-design simulations produced by the designers of the Interlock House.

3.1 Measurement Collection and Analysis

The house has been outfitted with a large number of interior and exterior sensors, which collect minute-by-minute data of a variety of information ranging from plug loads, temperature, light levels, to atmospheric conditions. Each sensor has been positioned into a permanent location based on manufacturer recommendations. This information is then fed into a data logging system, which sends information to the research computers at Iowa State University. This report uses illumination data from three photometric sensors located on the bedroom built-in desk, kitchen counter, and a desk in the kitchen positioned to face the south window. All three surfaces are roughly 2.5 feet above the ground, and light sensors are adhered to the surface. Occupants have been directed not to block the sensors, and to report if they notice any abnormalities. Radiation levels were recorded from a sensor located on the top of the house, which records the entire spectrum of light in Wm^2.

3.2 Simulation

As the solar home design progressed, lighting simulation tools were used to optimize the house illumination and energy performance. The simulations were developed by balancing a range of house performance variables, in order to achieve the most high performing and energy efficient design. The software performed an analysis of the home based on the lighting fixtures, geographical information, and atmospheric conditions.

Special attention was given to the bedroom desk, which aimed to maintain a 50 foot candle (approx 500 lux) light level through clear, cloudy, and partly cloudy weather conditions. This had been required for one of the Solar Decathlon contests based on office lighting requirement standards (ASHRAE/IESNA Standard 90.1 2007). It is important to acknowledge though, that the students performing this simulation analysis focused specifically on the daylighting performance in terms of the 2009 Solar Decathlon competition rules. Although the study thoroughly evaluates performance on cloudy, partly cloudy, and sunny conditions from 6 AM-5:30 PM, the analysis was only executed for one day (October 15) for the site of the competition at the National Mall in Washington DC. As a result of this decision, the solar home was adjusted for optimal performance at a location that is 3.2° to the south from the Interlock House's permanent location at Honey Creek Resort. This decision was made before the ISU Solar Decathlon team had arranged for the Iowa DNR to place the Interlock House at Honey Creek Resort. Washington DC was the only certain geographical location available to them at the time of the simulations.

The computer simulations were also carried out during the fall season, which is not considered an extreme lighting scenario; the sun is neither too low in the sky as it is in the winter, nor is the lighting performance affected by sun shading devices in the summer. This means that the simulation light readings that are available were done in response only to the house's spatial design, and does not factor in real occupancy variables such as shading fixtures. Factors that were included in the simulation were direct light, indirect light, transition zones that bring inter-reflected light, and the effect of surfaces. This type of analysis is optimal for measuring daylighting performance specifically, but is not an accurate representation of real living conditions. For most analysis programs, factoring in details such as the furniture and fixtures would require not only complex data computation, but would also ask for a lot of time invested by the designer to model individual furnishings. It is unrealistic to expect an exact match between these simulations and data collected from the actual solar home. Figure 5 demonstrates how factoring in shading devices and normal occupant patterns affect the lighting performance predictions made by the 2009 computer simulation done for the competition.

The shading device factor for this assumption derives from the actual house performance measurements. By comparing the ratio of light admitted into the kitchen before and after the window louvers were moved to the side, an assumption can be made about the influence of louvers on illumination readings. The impact of shading devices on the pre-design simulations is a measurement that took place post-construction in order to accurately gauge the effectiveness of simulations compared to actual performance data.

As a result, it is a valid assumption to use post-occupancy measurements to calculate the role of shading devices on pre-construction daylighting simulations for the purpose of determining simulation accuracy. The light readings from the computer predictions with and without shading devices reveals less distributed, more zone based lighting effect when shading is present. Section 4.1 and 5.1 will further discuss the similarities and differences of preliminary light modeling and building performance.

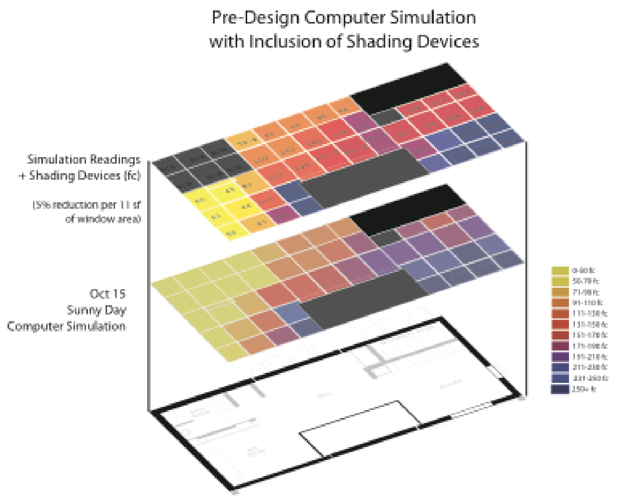

Fig. 5: Pre-Design computer simulations with the inclusion of shading devices.

The lighting performance during the competition and discrepancy with the lighting calculations suggested to the Iowa State researchers that upon its arrival to the resort, the Interlock House lighting design may not be adequate to function comfortably as an office. The following performance data and occupant behavior counter these predictions.

3.3 <u>Survey Development</u>

Although not yet collected, occupant feedback will be an integral part of understanding the Interlock House performance in a qualitative way. A questionnaire was developed after performing a literature survey of previous studies about solar home design that make use of questionnaires. A study that most specifically resembled the Interlock House and the research goals was identified (Pilkington, Roach, and Perkins, 2011), and used as a model for survey development.

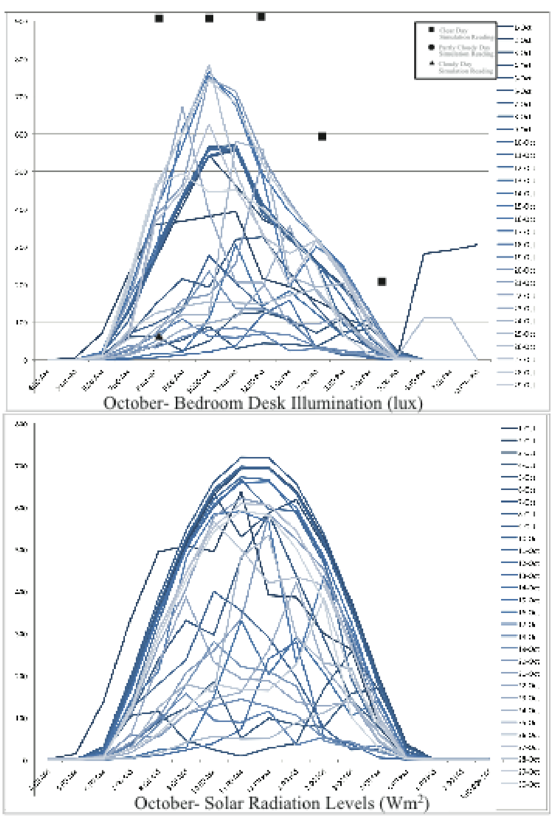

Fig. 6: Radiation and illumination patterns from bed-room light sensor (October 2012)

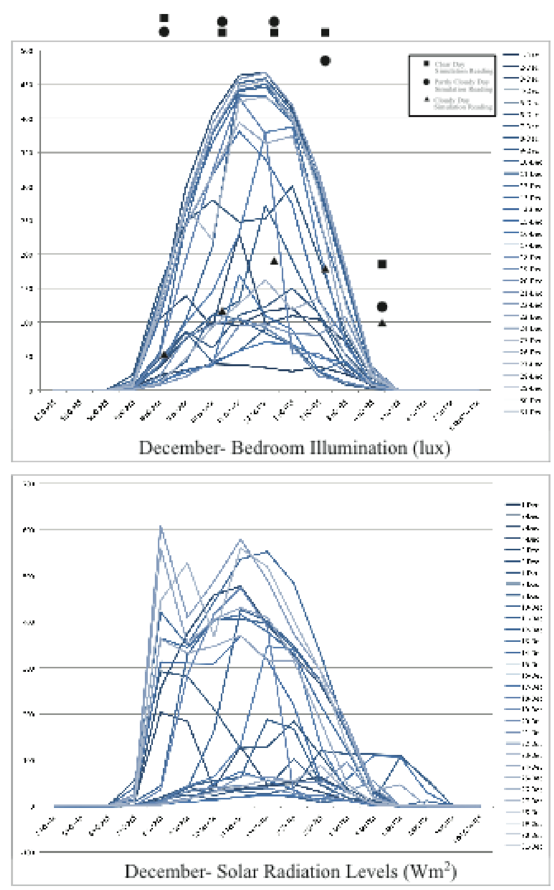

Fig. 7: Radiation and Illumination patterns from bed-room light sensor (December 2012)

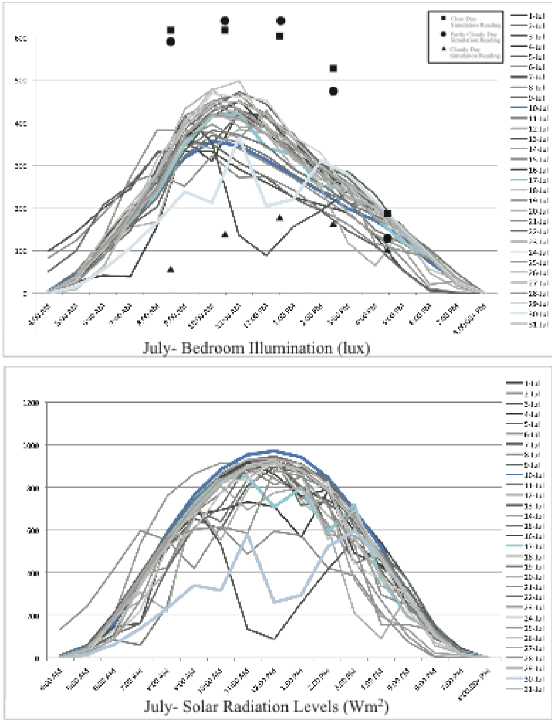

Fig. 8: Radiation and illumination patterns from bed-room light sensor (July 2012)

Each question has been formatted to prompt the occupant to respond to questions based on recent events, and is written in informal language. Occupants will begin the questionnaire by providing information about themselves followed by the request to recount days when they experienced comfortable and uncomfortable environmental conditions. The survey will end with a series of questions asking for occupants to rate their satisfaction, and a brief response about how the solar home and data collection has affected their work.

4. BEDROOM DAYLIGHT PERFORMANCE PATTERNS

Using the photometric light sensor positioned on the bedroom workstation, the Interlock House datalogger recorded the daylight performance on October 15. This study will also evaluate the effectiveness of 3 days with cloudy, partly cloudy, and sunny conditions during both July and December. The three months of study will serve as representations of annual daylight performance during times with a high sun altitude, low sun altitude, and a halfway point. This seasonal evaluation will set the groundwork for the discussion of perceived daylight effectiveness in the currently occupied Interlock House.

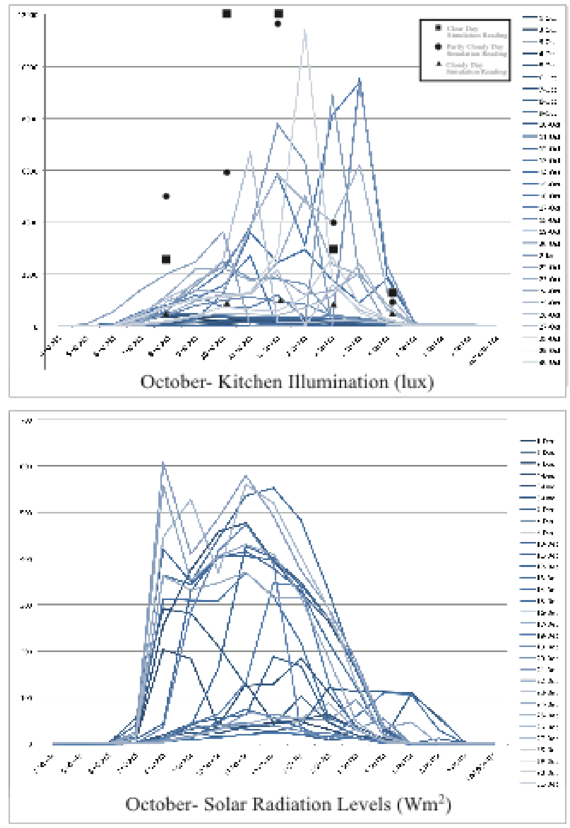

Fig. 9: Radiation and illumination patterns from kitch-en light sensor (October 2012)

Fig. 6 displays how widely the building simulation differs from the performance measurements collected from October 2012 for the kitchen and bedroom desk locations. Sunny days are evident in radiation measurements, as the measurements steadily follow a regular sun angle path. The bedroom desk displays similar evidence of illumination patterns reflecting full illumination from a clear sunny day, while the kitchen desk receives a more sporadic range of sunny day illumination readings and more consistent low-level readings.

The regularity in illumination readings reflects a success in consistent daylighting design, yet the readings are still below the intended readings from the daylight simulation program. On overcast days, the kitchen does achieve the intended illumination performance, but radiation patterns indicate that skies were mostly clear during October 2012.

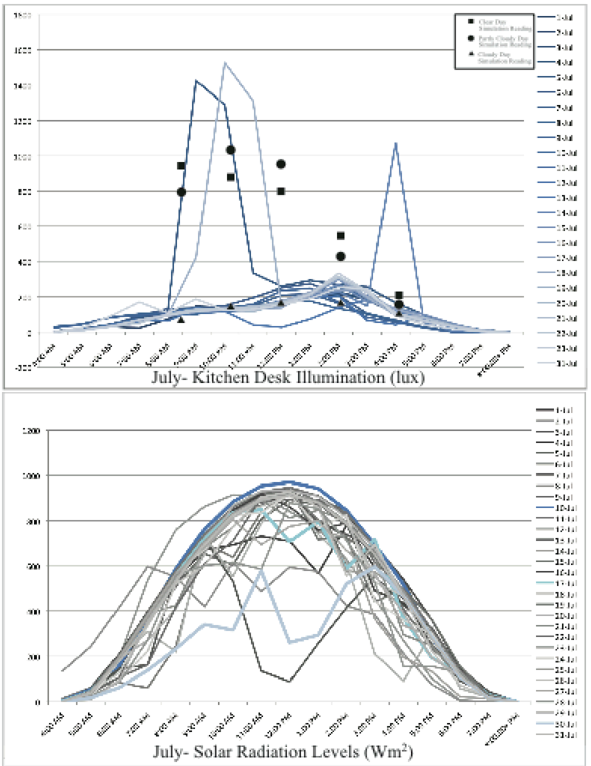

Fig. 10: Radiation and illumination patterns from kitchen light sensor (July 2012)

4.1 Seasonal Illumination Trends

The data from October offers a valuable representation of how effectively the solar home's performance compares with the simulations from 2009, but October is not typically characterized by extreme daylight conditions in the Iowa climate. Results from December depict how the radiation extremes tended to be higher than the normal 'sunny day' distribution that is present in radiation patterns from October. As a result, the illumination readings now read higher than the illumination numbers from the daylight simulation program. The bedroom illumination appears to be lit with a more even distribution on sunny days, which suggests that the shading devices that were blocking light in October are not shielding the bedroom from the winter sun This is also likely a result of the location of the Interlock House being more northern than what was anticipated by designers.

The month of July follows the pattern of higher, more consistent radiation patterns with lower, more distributed illumination in the bedroom.

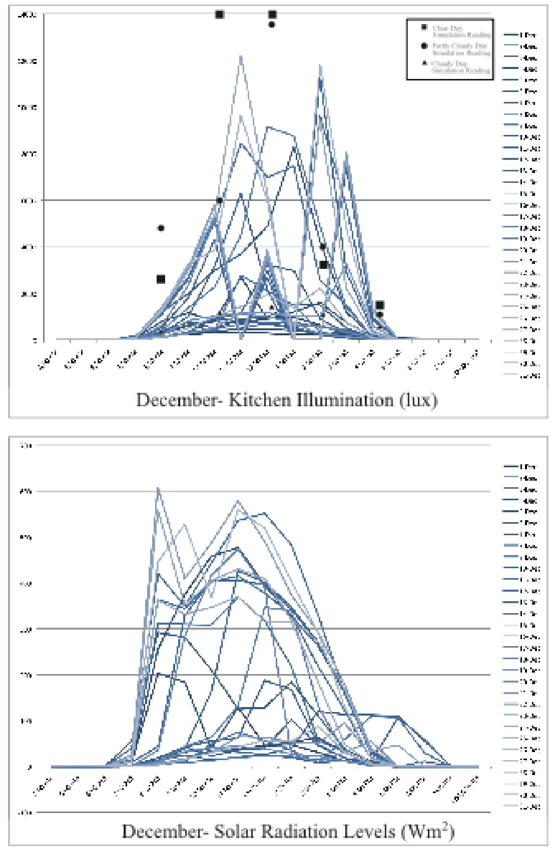

Fig. 11: Radiation and illumination patterns from kitchen light sensor (December 2012)

4.2 Proposed Survey Questions

The following are portion of survey questions relavent to the bedroom illumination quality that will be distributed to the occupants:

- How would you describe the nature of your work?
- How many hours a week do you spend working at your desk? If possible, please indicate during which hours of the day you typically are working at your desk
- Please describe a day that you remember it being cloudy or stormy. What kind of adjustments did you have to make in order to effectively work in the solar house? When and where did you make these adjustments? Please provide detail.
- When you come to the house in the (morning/afternoon/evening) during the winter months, how often is there not enough light? How often is it too bright?
- How does the bedroom office space affect your ability to get your job done?
- How has working in the Interlock House affected your productivity?

4.3 Research goals for Bedroom Illumination Performance

The data collections from the bedroom prove that the space is entirely lit by daylight in a consistent way on sunny days through the seasons. The occupant questionnaire will be the crucial ingredient towards understanding what makes this space a comfortable and functional one. Asking questions which give occupants an opportunity to give very specific examples of discomfort will help understand what impact the extreme readings collected by the datalogger.

5. KITCHEN DAYLIGHT PERFORMANCE PATTERNS

Similar to the bedroom desk, the kitchen workspace was also outfitted with a photometric sensor positioned on the kitchen desk. This sensor was places almost directly against the window, as the occupant has the work surface pushed up to the window. Due to this interior furniture arrangement, more adjustment is needed in this space to achieve a comfortable work environment. Fig. 9 demonstrates the light readings taken from this location closer to the southern window, which shift more drastically than its bedroom counterpart. As stated earlier, the kitchen desk achieves the illumination goal on a few days during the month of October, but the illumination is more consistently lower than the predictions generated by the lighting simulation program.

5.1 Seasonal Illumination Trends

The intense sun characteristics of summer months in July are evident in the radiation patterns shown in Fig. 9. The house design performed the most effectively during this month due to the high sun altitude and generally clearer skies. July is the only month in which the data logger collected illumination readings that meet the light levels for which the house was designed for. This observation provides a better understanding for how well the Interlock House would have performed if it were located in lower latitude, as the house was originally designed for. Lower latitude would have meant the sun angle would be higher during a larger part of the year. The consistent and effective light readings seen in Fig. 9 would occur more often during the year. An opportunity is also opened up for studying the range of latitudes for which a solar home can be designed with effective daylighting.

5.2 Research Goals for Kitchen Illumination Performance

The readings taken at the kitchen desk during July 2012 provide a valuable point of comparison for the occupant survey. If the occupant indicates that this month was not a month with comfortable daylight, it will be clear that the design illumination setting was designed for was too high.

5.3 Proposed Survey Questions

The survey questions which will be given to the employee occupying the kitchen desk are exactly the same as the questions asked of the bedroom desk occupant. See section 4.2 of this paper for proposed survey questions.

6. DISCUSSION

Visitors to the Interlock House often comment on the beautiful daylight design and the resulting spaciousness of the home. The collected data supports the success of the design intent to provide homogenous daylight from the north clerestory windows free of glare. The movable aluminum louvers have also proven a useful mitigation device. The data starts to suggest, that 50 fc (500 lux) is not the tolerance threshold, which leads to the activation of the lighting switch. The planned occupancy questionnaire will bring further proof of the assumption, that daylighting illuminance levels can be lower and still considered comfortable working environments.

7. ACKNOWLEDGMENTS

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