Proposed Framework for Daylight-Focused Homes during Design Development

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Abstract - Solar decathlon is held biannually, and participant universities have a unique chance to locate solar houses on campus as a living lab after the contest. A variety of performance criteria are evaluated during the contest and daylighting is one among them. Complicated analysis tools, design solutions, and their effectiveness are major challenges during the design development of new solar houses. This challenge definition leads to developing a daylighting guideline for new solar house design. To provide a roadmap of validity of emerging daylighting metrics, demonstration of the daylighting performance of built-up solar houses, and daylighting guideline for design parameters with recent technology on new solar house design are the specific objectives of this study. The manuscript aims to examine the existing daylighting design tools while proposing a roadmap for how to use emerging metrics over solar house design. Three solar decathlon entries of Missouri University of Science and Technology are selected for post-occupancy evaluation to verify selected design tools. After analyze method, tools and final products are introduced which can be used on case studies, impact on research and education is discussed in the paper. Experiential method proposal for daylighting design have three phases and these are; the daylight metrics, the daylight performance and impact on research and education. It would be beneficial in the future to have this as a design guide, especially for any residential buildings rather than just solar houses.

Keywords: Solar House, Daylighting, Design Tools, Performance Measurement

1. Introduction

The proper daylighting design optimizes the use of natural light in order to reduce lighting energy costs and maximize the visual comfort of the indoor environment [1] [2] [3] [4]. A well-daylit building can provide significant energy reductions and reduced operating costs for building owners of not only new construction projects but existing facilities. A well-designed day-lit building is estimated to reduce lighting energy use by 50% to 80% but must evaluate and balance the impacts of heat gain/loss and glare control [5] [6]. In addition to energy efficiency, a well-daylit building allows for the occupants to have an enhanced level of visual acuity, along with an overall increased psychological, and biological well-being and productivity [7]. Five definitions can be used to define what daylighting is; architectural and visual, lighting energy savings, reduced energy consumption, load management, and cost optimization [8]. Daylight has become directly associated with human health, life comfort, and effectiveness at work [9] [10] [11]. Glare, or excessive brightness contrast within the field of view, is one aspect of lighting that can cause discomfort to the occupants of a space [12]. To balance occupant comfort and energy concerns, the amount of daylight should neither be too low nor excessive [3]. In poor visual comfort conditions, a person can experience distracting symptoms such as red and itchy eyes, headache or back pain associated with bad posture trying to compensate for uncomfortable illumination [4].

Many different tools are available today for daylight analysis. These tools range from simple methods such as the use of sun path diagrams, daylight factor charts, and simple rules of thumb to advanced methods such as software packages of varying degrees of accuracy and physical model studies with artificial skies and/or heliodons [3]. The intention is not to compare and judge tools against each other, but rather to provide a resource for researchers who are interested to learn more and/ or need to make a choice about tools for solar design [13].

This paper targets to examine daylight-focused solar house design by using emerging metrics and propose a framework for based-on this study. The paper split up in three steps to come with a solution through proposing a framework.

Hypothesis, aim and content of this study is introduced in second part; daylight-focused solar house design. Based-on this framework, an experiential method with different steps is proposed in third section. These phases are defined as following; the daylight metrics, the daylight performance and impact on research and education.

2. Daylight-Focused Solar House Design

Smart living is a trendy technological development in building science based on primarily energy efficiency, human health, and well-being. Creating a controlled indoor environment for occupants is a major concern in this research field. Daylighting is one of these aspects in terms of visual comfort, human health and well-being, and building energy efficiency. The concern about daylighting is not new, dating back to ancient times. Advances both in predictive modeling as well as advanced techniques have emerged in an attempt to effectively improve daylighting integration. The use of these tools provides rapid and accurate prediction methods. There are two main problems related to daylighting in a smart building; 1) the complexity of emerging metrics resulting in slow adaptation within the building community and, 2) the hardship over monitoring the effectiveness of daylighting design solutions in custom design homes. Consequently, the problem is narrowed and defined in the intersection among three parameters as a design solution, effectiveness, and analysis methods (Figure 1). Computer simulation, physical model analysis, and post-occupancy assessment will provide the necessary data to evaluate the daylighting performance of a building during design development. The challenge definition is set in a triangle focused on daylighting. The relationship of the challenge to sustainability can be described as the following: contribution to pollution prevention or control, facilitating building energy efficiency and environmental sustainability, bridge building sustainability to human health and well-being, and benefit the healthcare industry and the smart building system market.

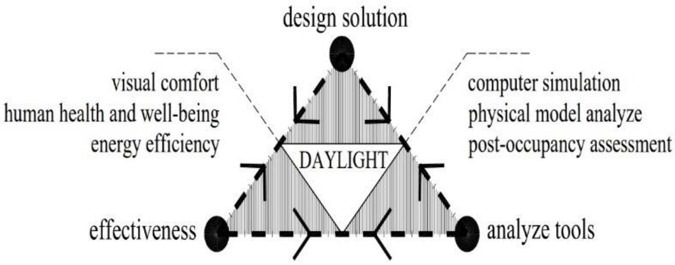


Figure 1: Challenge definition for the proposed system

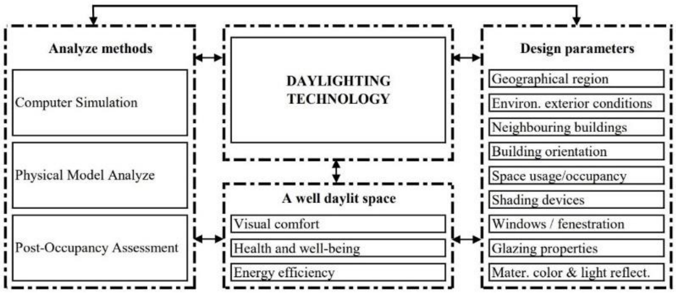
Solar decathlon is performed once in two years in the US, and it has both research and educational contribution to energy-efficient home design. These efforts can be split up into two; the first one is previously completed solar houses that have tenants inside that need post-occupancy evaluation. Qualitative and quantitative measurements can be performed by using different methodologies to assess the daylighting effect on visual comfort, well-being, and energy performance. The second one is ongoing design development for the upcoming solar decathlon. It is important to note that, a roadmap or a guideline of daylighting design answers to frequently asked questions during solar house design based on previous experiences would be beneficial to improve daylighting features of new solar houses prepared for the upcoming decathlon.

The hypothesis of this paper is "current and emerging metrics for daylight analysis tools can aid solar house design to provide better daylight performance during design development". According to the mentioned hypothesis, the purpose of this paper is to evaluate the usability of daylighting metrics during design development from the architectural engineering's point of view.

The research aims to investigate, develop, and deploy a daylighting model for sustainable and healthy indoor environments. The goal of this research is "saving a piece of the world by integrating daylighting through the use of emerging metrics in our buildings". The specific objectives are to complete the following: 1) validity of emerging daylighting metrics, 2) demonstration of the daylighting performance of solar houses, and 3) daylighting guideline for design parameters with recent technology on new solar energy house design.

This proposed daylighting model provides the performance parameters for a good daylight space in solar houses. With the help of emerging daylighting metrics, this project will measure primary design factors/parameters that directly affect indoor environmental quality. Design parameters related with the exterior environment are geographical region, natural and built environmental exterior conditions, neighboring buildings and building orientation. Others such as; space usage, shading device, window, glazing properties, material color and light reflectance are related with interior parameters. These design parameters can be measured utilizing analysis tools and these tools can be grouped into three categories: computer simulation, physical scaled model analysis, and post-occupancy assessment. The framework (Table 1) illustrates how each section of daylighting technology interacts and performs.

Table 1: Framework of the proposed system



3. Experiential Method Proposal for Daylighting Design

Analyze tools as daylighting metrics help design development of solar house. To do that, a complex analyze methods shall be performed in a sequence. Based-on specific objective of this paper, three analyze method as computer simulation, physical model analyze and post-occupancy assessment are needed to be investigated and developing a methodology is a necessity to meet the ultimate target. This paper is mainly focused on showing the method proposal for a daylighting design. As part of this research, an experiment is proposed over built-up solar houses, and metrics are needed to be defined. The proposed methodology is split up into three phases, these are daylighting metrics, performance measurement, and impact over research and education. Proposed phases and targets are depicted in Table 2. Targets show up in this table that needs advanced study and shall be discussed separately as future research.

Table 2: The proposed method for research development.

Phase 1		Phase 2	Phase 3
The daylight metrics		**The daylight performance**	**Impact on research and education**
a	Qualitative and quantitative metrics to measure daylight performance	Daylight performance of the built-up solar house	Guidance over design for new solar houses
b	Daylight metrics for post-occupancy assessment	Validation of emerging metrics	Adoption of results into education

3.1 The daylight metrics

Emerging metrics besides current metrics, make more complicated measurements of the daylighting performance of a building which needs expertise in different fields such as computer simulation, photography, solar path, etc. As a research field, the integration of these diverse performance measurement tools needs further study which means open to new researchers. The daylight metrics can be categorized into two as schematic or early design phase and the design development phase which is derived from the traditional project development process (Table 3). Current metrics are mostly used in the schematic design phase and emerging metrics are used in the latter one.

Table 3: Daylighting metrics during schematic/early design and design development phases

Schematic Design		Design Development
1	Solar paths analyze	Computer simulation
2	Massing studies & daylighting metrics	HDR imaging technique
3	Sunlight shading calculation	Heliodon analysis with a physical model

Daylight calculations have been started at the Northern European countries. Sky conditions in these countries are mostly cloudy sky. Therefore, overcast sky model is widely used in daylight calculations. However, as you get closer to the equator line, the use of overcast sky model will not provide a reliable data for these regions. The glare level in Zenith will increase as a result. However, in this study, overcast sky model is accepted in order to meet minimum requirements. Sky conditions in daylighting calculation is another topic to be investigated and discussed which is out of topic of this research.

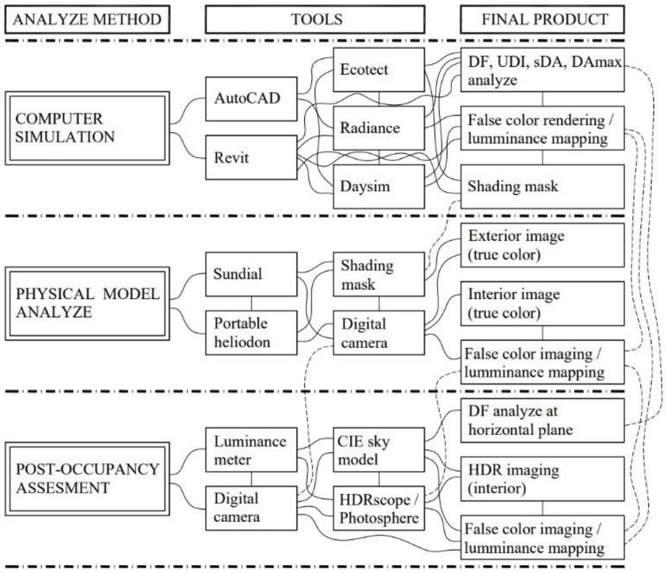
The oldest daylight availability metric is daylight factor, defined as the ratio between the illuminance at a sensor point inside the space to the illuminance at an unshaded, upward facing exterior reference point, under CIE standard overcast sky conditions. The most common computer-based evaluation of daylight availability to date begins by defining a grid of upward facing sensors offset from the floor (usually at desk height) followed by an evaluation of the daylight at these sensors using various criteria/metrics [3]. The annual amount of daylight in a space can nowadays be quantified via so called dynamic or climate-based metrics. As the name suggests, these metrics are derived from annual illuminance profiles, i.e., hourly or even sub-hourly time series of interior illuminance or luminance due to daylight that are generated using a local climate file [14]. Current and emerging daylight availability metrics are daylighting factor (DF), useful daylight illuminance (UDI), spatial daylight autonomy (sDA), annual sunlight exposure (ASE) and these metrics are used to meet criteria of LEED v4 and lighting measurement protocol by Illuminating Engineering Society of North America (IESNA) [15]. Daylight autonomy (DA) is a climate-based metric defined as the percentage of occupied times in the year during which minimum, program-specific illuminance levels can be met by daylight alone. The IESNA committee currently favors a target illuminance 300lux for offices, classrooms and library type spaces, occupied hours from 8 am to 6 pm local clock time. According to the IESNA lighting measurement, a point is considered to be “daylit” if the daylight autonomy exceeds 50% of the occupied times of the year [3]. Another climate-based metric called useful daylight illuminance (UDI) was introduced by Mardaljevic and Nabil in 2006 [16]. UDI largely resembles DA but defines lower and upper illuminance thresholds of 100lux and 2000lux for daylight to be “useful”. Due to the two levels, each point in a space has three UDI values: the percentage of the occupied time when the illuminance at the point is below 100lux, above 2000lux or in between [3]. In order to run these daylight analyzes, computer simulation, hdr imaging technique and physical model with heliodon are the tools to provide final product.

A daylighting study can be organized into three categories analysis method, tools, and final product. Since, considering the built-up solar house as a case study, analysis methods are addressed as computer simulation, a physical scaled model with heliodon, and post-occupancy assessment. Post-occupancy assessment needs illuminance measurement at desk level in a defined time-period. Proposed analysis tools and interaction with each other are graphically illustrated in Table 4.

Due to the complexity of the interaction of these metrics, daylighting analysis has not been widespread in practicing communities, and it is mostly considered a subject among researchers. It is obvious that this interaction shall be verified by performing a case study on the built-up solar house. Strengths and weaknesses of this interaction workflow in

Table 4 need to be discussed based on further research findings.

Table 4: Proposed interaction of emerging analyze tools and final products for advanced daylighting study over solar house.



3.2 *The daylight performance*

The U.S. Department of Energy Solar Decathlon is an international collegiate competition made up of 10 contests that challenge student teams to design and build full-size, solar-powered houses. The competition committee expects teams to blend design excellence and smart energy production with innovation, market potential, and energy and water efficiency. The first Solar Decathlon was held in 2002 and the competition has since occurred biennially [14]. Daylighting performance of a solar house also affects its excellence of visual comfort, well-being, and energy efficiency. Missouri University of Science & Technology has participated solar decathlon several times and the buildings were relocated to their permanent lots on the campus called solar and eco-village consecutive years after the contest. The region is coordinated at N37 and W91 in terms of latitude and longitude. The topographical terrain can be accepted flat even though there is slight slope existence which can be negligible. Solar arrays at roof are faced through south direction in general. Three of them were selected as a case study for daylighting performance measures. Design initiatives are different from each other and each has a unique concept in 2009, 2013, and 2015 (Figure 2).

Figure 2: Solar decathlon entries of Missouri University of Science & Technology; 2009 (left), 2013 (center), 2015 (right) [17]

Building orientation, fenestration system, shading design, and interior spaces follow up concepts and result in a different visual effect on the human eye in terms of daylighting performance. These homes are living labs for prospective research on sustainability and daylighting. Hence, the measurement of daylighting performance of these built-up solar houses can provide valuable data as research findings and results can be compared with each other. Moreover, the comparison may provide deviation/accuracy of applied daylighting metrics based on a proposed case study.

Table 5: Proposed tasks and outputs

Tasks		Computer Simulation	Physical Model Analyze	Post-Occupancy Assessment
1	Investigate DF or DA level	X		X
2	Develop luminance mapping	X		X
3	Explore shading mask	X	X	
4	Construct scaled model		X	
5	Validate heliodon and sundial setup		X	
6	Validate HDR imaging			X

Based on proposed interaction of emerging analyze tools in Table 4, detailed performance tasks and outputs are shown in Table 5. Outputs are scheduled in different levels as computer simulation, physical model, and post-occupancy. Impact on research and education can be measured by using the data provided by this research.

3.3 Impact on research and education

a. Daylighting guideline for design parameters with recent technology for new solar houses

Emerging metrics on daylighting technology in recent years have provided some new tools to the building designer. The problem is how to make use of these technologies in the overall daylight integration. The proposed model is to develop an educational toolkit on different building programs for residential use. Missouri University of Science & Technology is in a unique position as it has participated numerous times in the Solar Decathlon which is held biannually by the U.S. Department of Energy since 2002. As a result, the university has a unique solar/eco-village that provides an ideal case study to develop a series of educational methods ultimately leading to a daylighting toolkit for building designers.

Prospective research findings of a daylighting analysis on solar houses will have a positive impact on solar house design development. Emerging metrics, the workflow of interaction, and analysis tools will be evaluated and verified by future research. Building orientation, and window direction such as south and north windows, overhang, and shading devices will be compared. Furthermore, provided data can be used for integration with smart living features. Since, daylighting is more popular among researchers, rather than practicing communities, research findings will contribute to the research community. On the other hand, results will be a guideline/roadmap for designers who engage with solar house design for the upcoming U.S. Solar Decathlon.

b. Curriculum development

The results of case studies will also help daylight technology education by improving course curriculum, material, and assignment contents. Students will actively involve in daylighting design by preparing a term project which follows the workflow of analyzing tools used in proposed case studies. Based-on motivations on research background, a daylighting course part of sustainable design and smart living would provide valuable perspective to architectural engineering education. Since the entries to Solar Decathlon are performed through student participation, the curriculum development will provide positive impact on experiential learning.

4. Conclusion

The popularity of sustainable and energy efficient building design result-in development of diverse sub-trade expertise such as daylighting. Being still new research field, variety of luminance measurement methods are developed, and some are classified as emerging metrics. These metrics are popular in research community but needs to be widespread in the practicing community as well. The challenge definition shows how to design solutions, analyze tools effectively interact with each other. To aid solar house design in terms of daylighting context an experiential method is proposed. The paper presents the proposed phases of daylighting study which will be a roadmap for preparing a design guide for new solar houses. The research method proposed herein can be used in the future on new solar houses beside the existing ones in the world. Computer simulation, physical model, and post-occupancy are used during design development as emerging metrics, and validation of these metrics is proposed to be tested in selected built-up solar houses in Missouri University of Science & Technology campus. First, performance measurements of built-up solar houses are necessary to validate emerging metrics, and it is recommended to use this proposed methodology to apply over different built-up solar houses in the world. Secondly, it is recommended that a design guide can be generated based-on these findings, which will be used during design development of new-solar house design. The results of the research findings will be helpful to researchers and educators who deal with sustainability and energy efficiency. It would be beneficial in the future to have this as a design guide, especially for residential buildings rather than just solar houses. Furthermore, developing a daylighting guideline and curriculum development are concrete targets of this proposed method. Different phases of this proposed method need to be investigated and discussed separately. Qualitative and quantitative metrics to measure daylight performance (Table 2; Phase 1a) are determined and results are adopted into education (Table 2; Phase 3b) by developing an experiential course named "daylighting" in Architectural Engineering Program. Another paper will be particularly dedicated to the educational adaptation of daylighting design.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

References

[1] Osser, R. E., Andersen, M., Norford, L., (2007). Development of two heliodon systems and recommendations for their use. Proceeding of Solar 2007; sustainable energy puts America work. Cleveland, July 7-12, 2007. [Online] Available: https://infoscience.epfl.ch/record/153684
[2] Wimmers, G., (2009). Passive design toolkit for homes. Light House Sustainable Building Centre, Vancouver. [Online] Available: http://vancouver.ca/files/cov/passive-home-design.pdf
[3] Reinhart, C. F., Weissman, D. A., (2012). The daylit area: Correlating architectural student assessments with current and emerging daylight availability metrics. *Journal of Building and environment, 50 (2012), pp.155-164.* Published by Elsevier. [Online] Available: http://www.sciencedirect.com/science/article/pii/S0360132311003817
[4] Zaikina, V., (2016). Light modelling in architectural spaces; luminance-based metrics of contour, shape and detail distinctness of day-lit 3D objects. *PhD Dissertation*. Norwegian University of Science and Technology, Faculty of Architecture and Fine Art, Department of Architectural Design, Form and Colour Studies. [Online] Available: https://brage.bibsys.no/xmlui/handle/11250/2391667
[5] LEED, (2009). LEED reference guide for green interior design and construction. *US. Green Building Council (USGBC).* [Online] Available: http://www.usgbc.org/Docs/Archive/General/Docs9377.pdf
[6] Skripac, B., (2011). BIM for advanced daylighting analysis. Autodesk University. [Online] Available: https://sustainabilityworkshop.autodesk.com/sites/default/files/core-page-files/bimforadvanceddaylighting_skripac_au2011.pdf
[7] Heschong Mahone Group (HMG), (1999). Daylighting in schools; an investigation into the relationship between daylighting and human performance. *Pacific Gas and Electric Company*. [Online] Available: http://h-m-g.com/downloads/Daylighting/schoolc.pdf
[8] Reinhart, C. F, (2014). Daylighting handbook I; fundamentals designing with the sun. *Published in USA.*
[9] Boubekri, M., (2008). Daylighting, architecture and health; building design strategies. *Published by Elsevier Ltd.*
[10] Boubekri, M., (2014). Daylighting design: planning strategies and best practice solutions. *Published by Birkhauser Verlag GmbH.*
[11] Strong, D., (2014). Health, happiness, wellbeing & daylight. *3rd Annual GHA Conference, London*. [Online] Available: http://www.goodhomes.org.uk/downloads/events/David%20Strong.pdf
[12] Ander, G. D., (2003). Daylighting performance and design. *Published by John Wiley & Sons, Inc.*; 2nd edition, 2003, New Jersey.
[13] Horvat, M., Wall, M., (2012). Solar design of buildings for architects: Review of solar design tools. *Solar Heating & Cooling Programme, International Energy Agency.* [Online] Available: http://www.iea-shc.org/data/sites/1/publications/T41B3_approved-Jul12.pdf
[14] Reinhart, C. F., Wienold, J., (2011). The daylighting dashboard: A simulation-based design analysis for daylit spaces. *Journal of Building and environment, 46 (2011), No.2, pp.386-396.* Published by Elsevier. [Online] Available: http://www.sciencedirect.com/science/article/pii/S0360132310002441
[15] IES, (2012). Approved method: spatial daylight autonomy (sDA), annual sunlight exposure (ASE). *Illuminating engineering society (IES)*. New York.
[16] Mardaljevic, J., Nabil, A., (2006). The useful daylight illuminance paradigm: a replacement for daylight factors. Energy and Buildings, 38 (7), pp. 905-913. [Online] Available: http://www.climate-based-daylighting.com/lib/exe/fetch.php?media=academic:mardaljevic_udi_lux2005.pdf
[17] U.S. Department of Energy Solar Decathlon [Online] Available: http://www.solardecathlon.gov/