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State-of-the-art review of solar design tools and methods for assessing daylighting and solar potential for building-integrated photovoltaics

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ABSTRACT

Solar design can take many different forms across disciplines with different methodologies and goals, ranging from acquiring architectural visual effects to assessing illumination for daylighting and solar radiation potential on building surfaces for PV implementation. Furthermore, a capability of solar design methodologies and tools to accurately and time efficiently simulate light phenomena can greatly influence performance results and design decisions. This is especially important in complex cases such as dense urban settings with the significant surface shadowing, and vertical facades including daylighting devices and photovoltaics. Consequently, choosing a suitable approach and tool for each design phase is essential for achieving unique design and performance goals. This paper was carried out within the framework of IEA-PVPS Task 15 – BIPV and it aims to facilitate this decision for all parties involved in solar design process. Here presented, is an overview of almost 200 solar design tools, analyzing their numerous features regarding accuracy, complexity, scale, computation speed, representation as well as building design process integration in about 50 2D/3D, CAD/CAM and BIM software environments. Furthermore, tools from various fields have been analysed in a broad interdisciplinary context of solar design with a particular attention for being used for Daylighting and Building-Integrated Photovoltaics (BIPV) purposes. This approach should open many new perspectives on a potentially wider multidisciplinary usage and interpretation of solar design tools, sometimes well beyond their initial scope of work.

1. Introduction

Solar design can be generally considered as a process that involves simulation of natural light sources, namely sun and sky. It is used in numerous disciplines whether for artistic and scientific purposes in form of qualitative and quantitative analyses of surfaces and spaces with various spatial and temporal resolution and accuracy. Architects may use solar design tools for photorealistic visual representation helping them achieve specific light effects and atmosphere, emphasising design, objects' geometry and/or textures. On the other hand, in a collaboration with architectural engineers, architects may use solar design for climate-based annual daylighting simulations to achieve optimally-lit spaces and increase user comfort, balance solar heat gains to reduce energy consumption, estimate solar radiation impact on surface and air temperatures, assess solar radiation potential for BIPV installation, etc. Therefore, the solar design plays a significant role in the sustainable building design process as it influences building cooling, heating and lighting demand as well as carbon footprint, building energy consumption and environment impact. Ultimately, the solar design of renewable energy sources such as BIPV represents one of the essential strategies for achieving Zero-Energy and Zero-Carbon Buildings.

Light simulation capabilities directly influence accuracy of building performance simulation. Moreover, quality and level of integration in a design process make a great impact on a final building design. However, in its early phase of development, physically based light simulations were so complex and computationally expensive for the computational hardware. This has led to numerous simplifications and biased solutions. Since then, light simulations have evolved differently across the fields adapting to the industry-specific demands in order to overcome computational limitations. Most notably, the gaming industry has adopted fast hybrid path tracing algorithms with different level of bias in order to allow more realistic, real-time performance. Visualisation tools have put the focus on achieving photorealistic results implementing many biasing techniques to compute global illumination in time efficient manner. Daylighting simulations used daylight coefficient method, based on a hybrid ray tracing and matrix multiplication, for significantly reducing computation time for annual climate-based simulations with reasonable accuracy. Solar design tools for PV adopted analytical pre-computed Plane-of-Array method for

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calculating spot irradiance on PV surface and consequently PV energy output.

However, in recent years, increased computational power, especially GPU accelerated process, has allowed dramatic improvements, even real-time performance feedback, in solar design and particularly light simulation, paving a route for a dominance of numerical simulation and physically based ray-tracing solutions over the analytical, empirical or biased solutions. These improvements have allowed most of the solar design tools to expand their features to intervene across fields and eventually lead to integration of qualitative and quantitative simulations in building sector, as it has already happened in automotive and aerospace industries.

However, not all fields that use solar design tools have followed this trend of computational performance boost to improve design workflow and outcomes. This is evident in solar design tools for Daylighting and especially PV simulation where the improvement is moderate. For example, in comparison to the more advanced physically based lighting solutions from other industries such as visualisation, which are based on numerical algorithms, irradiance for PV energy calculation still rely mostly on analytical methods that are suitable only for basic PV typologies such as stand-alone and open rooftop solutions with wafer-based PV cell technologies. For other more complex environments that involve shadowing, advanced computation models e.g. ray tracing have to be considered for accurately assessing solar irradiance on PV surface and consequently PV yield. Regarding BIPV, most of the architects still consider their implementation mostly on their sustainability aspirations, economic benefit from feed-in tariffs and/or improving green rating, counting on their energy benefit. However, a multiple nature of the BIPV requires also a necessity for an integrated simulation approach in order to quantify their benefit and ensure proper implementation and economic feasibility. Unfortunately, commercially available tools offer simulation of particular performances to some extent, and yet there is still no 3d CAAD/BIM commercial tool that targets all types of BIPV (not only roof mounted), nor complex BIPV or even aimed for integration in architectural design or EDP. Existing methods for simulating BIPV are mostly custom processes and/or scripts used in research and/or very advanced engineering offices that connect some performances like energy yield simulation, thermal simulation with or without Computational Fluid Dynamics (CFD), or daylighting. Due to the limitation regarding paper's length, this paper focuses on solar design tools and methods for daylighting as well as solar radiation mapping for assessing BIPV potential. Consequently, topics such as BIPV energy modelling and building energy simulation are covered only to a certain extent where solar design is relevant. Moreover, this review is formed to provide general multidisciplinary framework to a specific, discipline-related topics. These two topics are planned for in-depth analysis in forthcoming reviews with a focus on energy savings and balance in a context of ZEB. They will be using part of the tools described here, relevant to each topic, while adding also dynamic simulation methods and tools. In order to address these topics, an international team of experts in IEA-PVPS Task 15-BIPV has devoted a specific task action on Design and Performance of BIPV. This paper was carried out within this framework and with a goal to synthesise multidisciplinary knowledge and methods in solar design and present roadmaps for further development of solar design tools to meet the demand of wide range of BIPV solutions, especially facades, considering also Daylighting as one unified approach. According to the task's vision, these advancements in solar design tools for BIPV and daylighting would enable architect to assess daylighting and BIPV energy production much easier, which will result in larger uptake and therefore acceleration of market growth for both BIPV and ZEB.

2. Previous reviews and surveys

There were numerous reviews in the past covering solar design and particularly daylighting simulation tools, mainly concerning simulation accuracy. One of the first comprehensive reviews on daylighting in buildings was done by IEA Solar Heating and Cooling Programme Task 21 / Energy Conservation in Buildings and Community Systems Programme Annex 29 and Lawrence Berkeley National Laboratory [1]. The main objective was to promote daylight conscious building design through the critical review of algorithms and existing tools as well as developing new ones such as ADELINE. Despite very advanced methods at that time, this review appeared at the early phase of daylighting simulation when computational power was not sufficient for the high computing demand of nascent advanced concepts such as Complex Fenestration System (CFS). Many tools presented there are not in use anymore, while many other have appeared over time. BIM was not developed at that time and CAAD integration was still at the lower level. Furthermore, the review was not comprehensive enough to cover detailed feature comparison.

Later, Reinhart and Herkel performed a state-of-the-art comparison of six Radiance-based methods for the simulation of annual daylight illuminance distributions using daylight coefficients calculation in a single raytracing loop [2]. The results demonstrated that it is possible to achieve acceptable accuracy in an annual daylight simulation method with significantly reduced simulation time.

Reinhart and Fitz conducted a web-based survey on the use of daylight simulations in building design [3]. Survey was realised by collecting 42 different daylight simulation programs that were in use at that time among 187 individuals from 27 countries. Over half of the tools were based on Radiance simulation engine, which confirmed its dominance in the field. However, the review was based on a questionnaire to understand trends, market share, needs, etc. Tools were not specifically indicated, neither their features to provide suggestions for new or to point out advanced features of all tools to existing daylighting specialist.

In 2007, Rogers presented an overview of daylight simulation tools covering 18 different daylighting methods including analytical ones [4]. Probably for the first time, features were presented in the matrix format that offered straightforward overview in comparison to the descriptive methods. Overview provided just a few tools/methods from each of the category of physical modelling, radiosity, forward ray tracing, backward ray tracing, climate analysis, sun path diagrams and other software. However, more importantly, the overview was interdisciplinary much broader than previous ones and included not only daylighting software but also solar design tools in general. In 2008, Galasiu and Reinhart published another web-based survey [3] providing insight into daylighting design practice with an explicit interest in sustainable design [5]. Again, similar information structure was provided, with an exception of including energy-related software. Practitioners clearly showed that quantitative solar design methods are used dominantly only in a design development phase and usually focused on energy savings. In 2009, Kota and Haberl published an interesting overview of the historical progression of the daylighting tools and tools used to assess daylighting in energy performance simulations [6]. Overview illustrated clear distinction between these two types of tools, concluding that energy simulations should incorporate state-of-the-art daylighting techniques for better assessing the solar impact on energy consumption. In 2012, Ochoa et al. gave a review of the lighting simulation for building science [7]. It was mainly based on a literature review and simulation models. Most importantly, it was noted that continuity and dominance of Radiance are good for the community but "focusing on one model might hinder the development of new ones". Moreover, integration of lighting simulation within general 3D modelling tools such as 3ds max was presented as an