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.

Keywords: "Building-Integrated Photovoltaics; Solar design tools; Daylighting; Light simulation; Physically-based ray tracing; Rendering; Complex BIPV simulation; Solar radiation mapping"

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 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 visualization, 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 modeling 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 interesting direction to address wider design-oriented public. In 2013, Iversen et al. conducted an investigation of the ability of nine daylight simulation programs to calculate the daylight factor in five typical rooms [8]. The analysis was based on daylight factor that was concluded not to be sufficient for a more complex lighting and scene situations. A sample of nine tools was compared in a matrix-based way, but still, the list was not comprehensive enough to cover majority of tools and features.

Reviews [9] and [10] raised the issue of scarcity of current BPS tools supporting the Early Design Phase (EDP). Reviews concluded that currently available Building Performance Simulation (BPS) tools are not compatible with architects' design methods and needs and are classified not to be 'architect-friendly' [11], especially emphasising difficulty of exchanging information between different tools without losing information and what's more creative continuity [12]. The common point for the majority of BPS tools is that they are suited

for the detailed design phase when most of the design is already defined and they serve to produce performance results and give a rating for one particular solution [13]. The gap between these two performance simulations methods is still vast, and there is a big space for improvement in terms of developing simplified models and tools aimed at EDP. This may explain why architects still widely use rules of thumb in the EDP.

Regarding reviews of solar design tools for PV, there are several studies related to this research scope. Freeman et al. [14] performed validation study for nine PV systems using the most common PV modelling tools: SAM, PVWatts, PVsyst, PV*SOL Expert. Like the majority of PV tools reviews, it was aimed for validation and comparison of tools' accuracy for free-standing PV solutions, not including shading. In addition, it provided valuable insight into tools' features in a matrix way. Moreover, the review showed that annual errors for detailed tools felt within ±8%, while PVWatts underestimated performances significantly with the default values, although with the calibration it could match other tools.

Axaopoulos et al. performed accuracy analysis of a different set of commercial tools: TRNSYS, Archelios, Polysun, PVSyst, PV*SOL and PVGIS [15]. Results showed that the PV tools' simulation generally overrate the Plane Of Array (POA) irradiation and underestimate the energy yield. It is concluded that the main cause of error comes from the model of the PV cell, and it was followed by an error caused by the conversion of the global irradiation on the POA. Moreover, PVGIS data may be considerably inaccurate, particularly if the simulation is performed on a month basis or short time periods. This is the confirmation that more advanced methods are needed for calculation of irradiance, preferably implementing ray tracing methods.

Freitas et al. [16] investigated a wide range of methods, from simple 2D analytical models to more sophisticated 3D representation and numerical analysis coupled with GIS tools, for modelling solar potential in the urban environments quantifying dynamic overshadowing impact on solar radiation availability. The review concluded that solar mapping tools, in general, are capable of dealing with some level of complexity while future improvements in diffuse radiation and energy conversion models are needed.

Finally, the most related state-of-the-art review is carried out within the IEA SHC Task 41 - Solar Energy and Architecture [17] [18] [19]. It was definitely the most comprehensive review done so far, with extensive descriptions for many software tools regarding solar architectural design that includes daylighting, visualisation, BIPV and 3D modelling tools. This was the first time that such, only seemingly different and diverse, topics were considered in the same review. Yet, this should be the only way for solar design to deepen its presence among the professionals by comprehending all interdisciplinary methods and improve integration. Hybrid concepts that emerge out of this integration will be the logical path for improving existing simulation tools' features and user satisfaction resulting in better and more sustainable building designs. In order to understand the relationship between solar and architectural design, the same task conducted international survey [19] [18]. This survey showed that currently available software and digital tools are not well adapted to deal with the solar strategies including BIPV simulation and more effort is needed to design new or improve existing tools. The review also clearly emphasised lack of "architect-friendly" tools for solar design, despite the variety of choices. Their survey and interviews undoubtedly demonstrated the necessity for the further development of design tools for solar architecture, putting a spotlight on user-friendly tools, preferably integrated into Building Information Modeling (BIM) environment, that present straightforward and meaningful results compatible with the architects' design workflow. However, despite the broad range of choices, review just marginally touches BIPV, only in term of BIM library element and only for visualisation purposes. Furthermore, overview demonstrated there is no common language for describing what the BPS tools do [20] leading to the confusion among architects unable to distinguish which tool would fit their working method best. Ultimately, all mentioned reviews have not taken into consideration some of the important features for complex BIPV such as spectral rendering, advanced light transport models and layered material definitions. In addition, vast amount of information was presented in a descriptive way so it is hard to make quick conclusions and comparison and find a particular feature.

3. Objectives and methodology

The review aims to overcome limits of previous reviews and provide the most extensive list of solar design tools and features across all industries that use solar design. The main objectives of such a comprehensive analysis of the interdisciplinary topic is to:
- describe the most significant features and workflows that are currently available;
- explain differences and similarities of objectives and workflows across multiple disciplines;
- provide insight into possible limitations and bottlenecks of particular functions, procedures and tools;
- map tools with features in visually structured way;
- offer quick and effective comparison that could be done in two-ways, per feature/category and/or per tool/discipline;

- understand market trends and current advancements;
- propose potential further cross-disciplinary integration and developments;
- target needs and facilitate decision-making of end-users from all backgrounds and level of expertise who are interested in learning and working in the solar design.

Intentionally, the review includes many disciplines that were not subjected within the same research before, eg. gaming and optical design. Author believes that this approach is essential in order to understand all parts of solar design and simulation workflow as well as light simulation models and concepts. Better understanding of universal cross-industry concepts will consequently lead to better implementation of current tools and demand for their more progressive improvements, especially regarding multidisciplinary approaches and integration.

Paper's methodology uses data collection that was performed through available official resources provided by software developers in various formats including web sites, manuals, white pages, tutorials, feature lists, etc. In particular, where solar design tool seemed interesting and advanced but feature description was not available, data was verified by mail communication with its developers. Specific feature may be implemented as a standard ready-to-use feature, directly available to the end user. However, feature may be available indirectly if software is open-source and there is a possibility for end-user to change source-code slightly, or available through graph-based parametric interface that enables object-oriented programming. These features are marked as tweaking possible. Otherwise, if feature is not supported, data field was left empty. If there is a doubt on feature due to the lack of available resources, fields were marked as data not provided.

Solar design tools presented in this review have different software structures. Some tools are designed only as collection of executables/modules that can be executed without GUI. Those tools represent core engines that other tools use for calculation while providing GUI. They are presented in legend together with a symbol that is assigned with every tool that uses that specific engine.

The review consists of descriptive and graphical - tables parts. Descriptive part explains all light simulation concepts sorted in categories, while tables provide more structured, compact and straightforward way of presenting vast amount of information on tools and features in the solar design process. They consist of solar design tools sorted in columns while features are listed in rows. Tools and features are sorted into categories according to their original area of development, as some of the tools have become interdisciplinary over time. In comparison to the previous studies, this review should be easier to understand, faster for comparison of particular features or tools of interest, easier for target searching and learning for more end users with different backgrounds and level of expertise. Most importantly, it should facilitate user decisions on most suitable software tool for the particular design phase and project goals. Moreover, solar design workflow has been constantly changing over the years, especially in the last decade, when influenced by new simulation tools provided significant improvements in speed, accuracy, integration in CAD and 3D environment and user friendliness. This review aims to understand these trends and provide guidelines for potential future development by suggesting possible cross implementation among fields in order to develop more robust simulation models that would be able to deal with highly complex topics such as BIPV simulation and daylighting including CFS.

Despite a huge number of tools included, there are still tools that are left out in each category due to the various reasons.

Tools in daylighting/lighting/solar analysis category: Desktop Radiance, ECOTECT, SUPERLITE, Delight, SKYVISION, Lightscape, are excluded from review due to several reasons: They are either not available anymore on the market or their support or future developments are revoked.

Whole building energy tools that did not fit into this review are: Ecotect, ADELINE, EnergyPlus, bSol, ESP-r, EnergyPRO, tsbi3, SUNCODE, EDG II, TRNSYS, ENERGIEplaner, DOE, eQUEST (DOE), VisualDOE (DOE), LESOSAI, BCVTB. Reasons can be found in: poor daylighting simulations, lack of integration into architectural design environment, developed for the detailed design phase, substantial knowledge is required to run the dynamic simulation that is out of scope of architectural design process, out of the market, support and future developments are revoked.

Advanced whole building energy as PV/BIPV tools, not covered here, will be a part of another review where analysed features will specifically suit advanced dynamic PV and building energy simulation.

4. Part I - Solar design concepts and features

Disciplines included here are daylighting (point in time and climate-based), whole-building energy, optical design, visualization/rendering (still images and movies/animations), gaming (real-time interactive visualisation/graphics), and partly PV/BIPV. Analysis of light simulation concepts and tools and their integration in design process are the two major parts of this research that goes well beyond previous reviews and cover the most successful concepts developed across fields. Furthermore, simulation engines/tools are surveyed for their methods of integration in common design software environment in the context of PBD, examined for their

ability to suit different design phases and various scales, from material to urban, availability in different operating systems and pricing. In the following subchapters, only the most important features will be discussed, confronting advantages and shortcomings of different methods. Other features, not described here, but presented in the review, are self-explaining and do not require detailed explanations.

4.1. Geometry

The review considers only tools that support 3D architectural content. Geometry in 3D can be generally represented in two ways: Shell/boundary objects that are represented as surfaces of the object and solid objects that represent objects as volumes. First typology is used more often in visualization and gaming industries while solid representation is used for scientific and engineering purposes in CAD/CAM and BIM tools. Another major difference between artistic and scientific modeling techniques is surface representation. Surface can be represented mathematically as analytical model or through curves, usually Non-Uniform Rational Bezier Splines (NURBS). This model is useful especially for engineering and manufacturing purposes as all surfaces can be described and analyzed with extreme precision. On the other hand, surfaces can be modeled as points in 3D space that are connected by line segments to form a polygon mesh triangles. This polygonal mesh representation was a dominant method for the majority of rendering engines due to the versatility and speed. NURBS were not supported in the early development stage of ray tracing and these surfaces had to be converted in polygon meshes, in a process called tessellation, before being rendered. That conversion could have produced undesirable results, especially in details, with artefacts visible in jagged edges appearance or voids. As CAD/CAM and BIM applications use solid based surfaces, any rendering of tessellated geometries might possibly produce artefacts and errors. While flat surfaces have low error possibility for producing conversion artefacts, freeform and curved surfaces have to be processed carefully, usually increasing density and number of polygons to make artifacts less visible. Until recently there was no rendering algorithm able to work directly on a solid geometry. This has been changed mostly in automotive and aerospace industry software such as Autodesk VRED, Luxion Keyshoot and Lagoa. Rendering directly this type of surfaces allows rendering with a great level of freedom and precision independently of scale. It is expected that rendering directly this type of surfaces will prevail also in CAD/CAM and BIM applications in the future.

4.2. Light transport models

4.2.1. Split flux formula

The split flux formula is the simplest and the oldest algorithm used in daylighting studies that was derived from a manual calculation method established by the BRE (The English Building Research Establishment). This method is consisted of three components of daylight: the direct sky component, the reflections from exterior surfaces and the reflections from internal surfaces. Components are calculated separately and summed to express global illumination in each sensor point. Results obtained are highly approximated and this model has been surpassed by more advanced computer simulation approaches. However, energy simulation engines like EnergyPlus and DOE are still using this method to calculate daylighting factor and energy consumption for lighting.

4.2.2. Rasterization (Scanline)

Rasterization can be generally defined as a process of converting or mapping fragments (3D objects, vector shapes) into the projection plane/image. This process uses a fragment-by-fragment (object order) approach where algorithm loops through each of the fragments, usually triangulated polygon meshes, and determining which pixels in the image it affects and modifies those pixels accordingly [21]. The most used version of rasterization firstly renders the vertices of a face and then interpolates the texture coordinate of that face as a blending of the vertex colours while neglecting specular lighting. This method is used by all current Graphical Processor Units (GPU) and represents de facto standard for real-time computer graphics, particularly games. However, the method is very limited in terms of calculating specular reflections. In order to overcome this issue, rasterization has been recently integrated with a ray tracing in form of a hybrid technique. Due to the rendering speed, rasterization was very common in the 3D animation industry. One example was REYES algorithm [22] that has been used for many years as a core of the PIXAR RENDERMAN before it was replaced by fully ray tracing approach.

4.2.3. Finite element methods - Radiosity

Finite element methods (FEM) originate from radiative heat transfer methods [23]. They have found their application in computer graphics field, in form of so-called radiosity methods [24] [25]. They were developed

mainly to account for non physically based but very time-efficient computation of the indirect illumination. In this process, scene geometry is tessellated into a number of small patches. These patches represent main sources of the global illumination where a global illumination is resolved by computing global rendering equation composed of a linear system of equations describing the light interaction between patches. Initial versions of radiosity were very limited to compute complex geometries, lights and materials of the scene. These versions were created for simple scenes with Lambertian (perfectly diffuse) surfaces and large area light sources. Such restrictions allowed radiosity method to be view-independent meaning that one computation can be reused for rendering images from arbitrary viewpoints. Creating more complex environments has remained a challenging task and this method has been constantly improving adding support for more complex reflections [26], as well as hierarchical methods to address complex geometries [27] [28] and instant radiosity [29]. However, these advancements made the radiosity algorithm much more computationally expensive, while not following real light behaviour, neither providing physically accurate and photorealistic appearance. However, the speed of calculation for simple scenes was still a great advantage. Only recently, methods based on radiosity, as in the case of rasterization, has slowly been abandoned in favour of ray tracing methods.

4.2.4. Stochastic (Monte Carlo) based methods - Ray tracing

Ray tracing is a rendering technique based on a geometric (ray) optic light model that calculate light transport by tracing a large number of rays in a scene - Path Tracing (PT). It originates from ray casting algorithm, developed to solve intersections of the rays with an arbitrary geometry including triangle meshes and mathematical surfaces such as constructive solid geometry models, which trace only one ray per pixel without recursively tracing additional rays needed for global illumination. Ray tracing is an advancement of this approach, originally proposed by [30], that calculate global illumination by means of recursive point-sampling based on rendering equation developed by Kajiya [31]. Rays in ray tracing follow the same principles as light in the real world and therefore this technology is the only one that can be considered physically based [32]. This comprehends that light transport follows energy conservation principles [33][34] with the every light bounce. In other words, at each level of recursion ray tracing algorithm can split ray into components for reflection, transmission (refraction) or in the case of participating media absorption and in particular cases emission, where a sum of radiosity values of the component part must be equal to incident radiosity. Splitting is controlled either by deterministic or stochastic[1]- Monte Carlo methods [35] [36] [37], essential for all path tracing methods. In a typical Monte Carlo numerical algorithm, random draws following given distributions define a chain of local events characterising the global event and leading to a final state. Therefore, exploring the solution space or events space by repeating random draws numerous times can give an accurate approximation of the solution. The accuracy of this numerical solution depends on the level of model description and number of samples and bounces. Simple and uniform random Monte Carlo sampling would be very impractical and therefore hybrid approach implementing deterministic sampling is always used to facilitate a decision on what to sample, or in other words where to trace the next ray [38]. Over the years, many importance-sampling techniques have emerged. Ultimately state-of-the-art method called Multiple Importance Sampling (MIS) [39] has made physically based rendering computationally feasible today. Particularly important for this research is the optimisation of MIS algorithms for the sampling complex materials, with custom Bidirectional Reflection Distribution Function (BRDF), and illuminated by High Dynamic Range (HDR) Images [40] [41].

Furthermore, shading and light on the surfaces is a sum of components coming directly from the light sources, as specular: reflection and refraction, and as diffuse indirect reflections. First two components can be handled relatively easily while the last one typically requires tracing hundreds, thousands or even millions of rays. Hence, this component is usually subjected to various levels of approximations and optimisations and it is generally considered as a bias. More on this is explained in subchapter 4.3 on accuracy.

Ray tracing can start either from light sources - forward ray tracing, or from a viewpoint or sensor - backward ray tracing or in advanced hybrid methods by combining these two – bidirectional ray tracing. Forward ray tracing methods are commonly used for the optical design of luminaries where it is important to estimate light distribution from the designed luminaries or light transport in optical systems of lenses. This is the ideal version of the light transport model that can simulate all light phenomena as it exactly follows real world light behaviour. However, the main drawback is that it is extremely costly in terms of calculation since for the smooth and pleasant results it has to trace millions of ray recursions while never being able to reach infinite recursions that happen in the real world. Furthermore, accounting specular reflections is a view dependent effect and it had to take into account a view position. Some of the leading forward ray tracing tools are SPEOS, TracePRO, and Photopia. These software are not designed for the general architectural usage and daylighting in general. Only

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[1] Stochastic method is one whose state is non-deterministic (i.e., "random") so that the subsequent state of the system is determined probabilistically

recently they have started to implement the sun as a light source like in Solar Utility feature of TracePRO and still require some tweaking in order to be implemented as a daylighting tool (Kolås, 2013). Yet, they are commonly used to produce BSDF function for Complex Fenestration Systems (CFS), but their price, closed source code and uncommon software environment for architects and building engineers represents a limiting factor for the broader implementation in building design process.

On the contrary, in the case of backward ray tracing, rays are traced from a camera viewpoint for rendering purposes or from (grid) sensor points for daylighting analyses. Backward ray tracing is much faster method for image synthesis and grid based calculation than forward ray tracing as it only calculates rays reaching the view or sensor point. Since the beginning of the CGI image synthesis, this method has been representing the standard for achieving physically based images for a long time. Radiance engine was one of the first backward ray tracers [42] [43]. Downsides of this approach are represented in the inability to handle complex reflections and refractions of surfaces with specular properties and caustic scattering in transparent materials and participation media. Furthermore, it is not directly suitable in handling properly scenes where light sources are hard to find, i.e. narrow light cracks, light pipes, CFS-like Venetian blinds and caustics.

Finally, both methods have some disadvantages and neither can efficiently solve complex lighting conditions, volumes and materials. Consequently, many hybrid techniques combining these two, have been developed over the years to address these issues, particularly Bidirectional Path Tracing (BDPT) [44] [45] and Photon Mapping [46] [47].

Photon Mapping firstly traces photons from the light sources and store them to be accessible during next rendering phase when rays traced from camera reads stored information for calculating diffuse part of indirect illumination. A progressive version of Photon Mapping has been recently introduced to Radiance to simulate the behavior of Daylight Redirecting Components (DRC), in order to support architects in assessing their performance [48]. This long expected extension will greatly help Radiance users in exploiting all benefits of the bi-directional approach.

BDPT is a combination of forward and backward path tracing. Although capable of dealing with complex situations, the main issue for the basic BDPT is excessive noise. This has been addressed by variety of improvement techniques such as Metropolis Light Transport (MLT) [49] [50], Gradient-Domain Bidirectional Path Tracing (G-BDPT) [51], Energy Redistribution Path Tracing (ERPT) [52], Gradient-domain Metropolis Light Transport (G-MLT) [53], Primary Space Simple Metropolis Light Transport (PSSMLT) [54] and particularly interesting Manifold Exploration Path Tracing (MEPT) [55]. Latter chooses mutation in paths to calculate specular regions and caustics and produce smooth results efficiently. This approach will be beneficial for all daylighting redirecting systems and optically active façade devices, like some BIPV that include light trapping techniques to absorb more light. It is already implemented in some renderers like Mitsuba [56] while others will certainly follow this trend.

4.2.5. Hybrid approaches

Worth-mentioning hybrid approaches include a combination of ray tracing with radiosity, or ray tracing with rasterization. First is used in some daylighting software tools such as EDSL TAS and DIAL+Suite and it offers some advantages of both approaches. An advanced version of this hybrid method uses Multidimensional Lightcuts [57], based on Lightcuts [58] and Instant Radiosity [29], to handle complex illumination and specular materials efficiently. This method is implemented in Autodesk 360 rendering engine used in Lighting Analysis for Revit, Solar Analysis Tool and Green Building Studio. Developers claim that this method is up to 10 times faster than Radiance. However, since indirect illumination is based on Instant Radiosity, a biased method that does not include caustics, which may be a significant shortcoming for CFS and complex BIPV.

Another approach is originally developed for the gaming industry and combines ray tracing with rasterization [59] [60] using very best from both techniques and delivers remarkable photorealistic performance in real time. In this method, rasterisation is used exclusively for antialiasing while ray tracing handles specular effects. Moreover, Brigade and Frostbite offer physically based BDPT that is mentioned as an advanced method able to simulate most complex scenarios. Yet again, other gaming engines still cannot handle caustics. However, the significant speed of the calculation can be very valuable in the early design stage of any lighting design and simulation. The majority of the gaming engines are already commercially available such as UDK Unreal Engine, Unity, Brigade Stingray or Cryengine. Despite the fact these methods are not designed for scientific purposes, some of them like Frostbite demonstrated great accuracy when validated against visualisation industry standard PBR engine Mitsuba [61].

4.2.6. Ray path preview

This is one of the most overlooked features that can be crucial in EDP, especially for qualitative inspection and design of CFS, DRS and shading systems' geometry, where ray preview can greatly help tweaking the

shapes and improving performances. While present in all forward ray-tracing tools like TracePRO, Photopia, SPEOS and Lumicept, it still represents advanced feature usually unavailable to the broader range of building industry users mostly due to the price tag and different design workflow. Photon Mapping extension to Radiance classic also have the ability to show ray paths [62]. It is recently been integrated into standard Radiance package. However, it will take time for other tools that are based on Radiance to integrate it within their design environment. Still, ray paths can greatly support design decisions in real time as user can immediately sees rays with most intensity and their direction to estimate the influence of light deflection on light levels, a feature very useful for complex BIPV and CFS.

One approach that uses Radiance for analysing Daylighting and clear view of a complex BIPV façade [63] implements mathematical formulas to design and treat geometrical aspects and layout of thin-films stripes and ray propagation through the medium to optimise angle dependency of the system. However, this is one of the rare cases where geometry layout is plain and mathematically defined. For other more complex cases, ray preview represents valuable assistance. Author's work in this field [64] shows how ray path preview has been used for real-time performance feedback in order to understand how geometry of saw-tooth glass profile influence daylight redirection and PV absorption. Furthermore, preview was used to decrease design search space for later optimization process thus reducing optimization time significantly.

4.3. Accuracy

4.3.1. Bias and consistency

Considering complexity of the light behavior and number of photon bounces in real world, only numerical solution that are physically based have a potential to be accurate to the extent that difference between simulation and real world values are negligible, in other words error approaches zero. There is often a misconception over the usage of terms un/biased and in/consistent. Unbiased is often used to represent particular rendering engine as physically accurate solution. However, this may not always be true as all ray-tracing solutions are biased to certain extent in a way that none of the tools can match number of bounces that happens in reality. Generally, all solutions have to overcome this limitation by introducing some techniques that reduces number of photons/rays and their bounces or give importance to some ray directions in order to generate results faster. Difference between unbiased and biased methods lies in the ability to produce correct results on average when combining multiple iterations. Unbiased will always produce results and errors that are predictable and proportional to the variance of the estimator and computation time [65]. Biased methods implement reasonable simplifying assumptions that improve efficiency. All techniques based on catching data of diffuse indirect illumination component are generally considered as biased. Additionally, adaptive sampling and value clamping using threshold to decide whether to continue a path may also considered as a bias. However, for the purposes of this paper and solar design tools in general, it is more important to differentiate consistency. Consistent method assumes that with an increase of computation time the approximation error approaches zero. This practically means that consistent method can reach any level of accuracy can by increasing the number of photons, reducing or decreasing noise threshold. Therefore, only techniques based on path tracing, bidirectional path tracing, volumetric path tracing and Metropolis light transport, sometimes called brute force methods, can be considered both unbiased and consistent. They do not use any pre-computation for computing diffuse indirect illumination component and catching data, and consequently their convergence to the unbiased final solution is significantly slower than others that use pre-computation. However, these techniques may also be biased if bounces of light are limited (photon bounces are stopped before they are completely absorbed or left the scene) and if caustics are not included in the computation.

Irradiance caching [66], originally implemented in Radiance, can be considered as a high-quality biased but consistent acceleration technique for computing diffuse indirect illumination component and it is widely used in many ray tracing engines and hybrid methods such as photon mapping. Its main advantage is that it incorporates the beneficial properties of radiosity methods while retaining the generality of Monte Carlo approaches.

Since it is impossible to distinguish accuracy of particular biased and unbiased implementation and solution generally, as tools offer different number of options to control bias, this review will therefore differentiate only all previously described consistent methods over non-consistent ones such as splitflux, rasterization and radiosity.

4.3.2. Validation

In order to evaluate the accuracy of the light simulation tools, the CIE technical committee 3.33 defined a set of test cases and methods [67]. Validation of these test cases has been shown in [68]. This research showed the usefulness of the proposed methods and cases in assessing the accuracy and the capabilities simulating different aspects of the lighting propagation by representing strengths and weaknesses of the light simulation tools.

However, it is noted that proposed test cases are not sufficient to address other complex lighting and daylighting cases. Various proposals have been made to improve evaluation of global illumination methods such as [69]. Reinhart [70] also proposed: "A complementary set of more complex daylighting test cases that compare experimental measurements in "real" daylit spaces with simulations is necessary to help design practitioners to develop a feeling of how close a lighting simulation program, operated by a knowledgeable user, can model reality". Physical validation of global illumination methods: measurement and error analysis

Additionally to CIE validation test cases, other datasets are available such as ones proposed by The British Building Research Establishment (BRE) and National Research Council Canada (NRC). The latter one is used to validate popular mental ray rendering engine within Autodesk 3ds Max Design 2009 as well as the Daysim 3.0 [71, p. 0].

4.4. Computation

Computation of light transport has always represented one of the most important features for light simulations. Lack of computational power during the first period has forced all methods to develop simplification models to be able to perform simulations in a reasonable time. Ray tracing, as ideal light transport version, has been waiting for a long time to become a dominant method. Ray tracing algorithms have firstly been designed exclusively for Central Processor Unit (CPU). Furthermore, early simulations in 80's were needed several hours or even days to obtain results. Single-core CPUs have followed Moor's law and progressing until they reached theoretical limits in speed of about 4GHz in 2005 due to the overheating caused by high frequency. Since speed was limited, the only way to increase efficiency was to use parallelism. Various strategies have appeared for multi-node parallel rendering such as replacing single-core with multi-core CPUs implementing hyper-threading, connecting CPUs and creating render farms over the local network, Cloud [72], or directly as "render slaves". However, this was not efficient and economic way of parallelism and improving efficiency as price vs. efficiency was directly proportional.

With the rapid development of GPU capabilities and speed, simulations have started to be performed also on GPU [73] [74] or by combining CPU and GPU. In order for GPU to become general-purpose hardware, specific drivers have to be created in form of APIs. NVIDIA uses its own API – CUDA, while AMD cards work with OPENCL APIs. Contrary to the OPENCL, CUDA is not card specific and works with all CUDA-enabled cards. Although CPUs are created as fast low latency solutions, initially optimized for single tasks, GPUs are designed for massively and embarrassingly parallel and independent tasks [75], such as calculating the color of each pixel on the screen [76, p. 1]. Luckily, ray tracing is one of these types of tasks and GPU based renders have started to emerge rapidly. Efficiency vs. cost ratio is much better in comparison to the CPUs, as for the small increase in price, performance can be increased multiple times. So far, the main barrier for GPU based renders has been memory that can be stored and accessed, because complex scenes require more memory, and therefore they could not have been rendered with GPU before. This was solved recently with the introduction of Pascal and Polaris architectures by NVIDIA and AMD respectively, as they provide cross-GPU memory access (NVIDIA NVLink) at very low latencies. Another advancement that will enable boost in efficiency is High Bandwidth Memory (HBM) configuration that stacks regular memory chips on top of one other and enables bandwidth of up to 1000GB/s. One approach that time-efficiently combines several methods relying only on GPU to perform unbiased physically based rendering is presented by Van Antwerpen [77].

Cloud-based computing has emerged with the dramatic increase of the internet speed over the past years. It allows hardware-independent solutions where there are no limitations of either computation power or hardware. In these terms, simulation is possible even on mobile devices and tablets. This is a major breakthrough for all the industries related to light simulation as it finally allows enormous capacity to perform simulations in real time. Alternatively, cloud computing may be used for numerous simulations of different solutions in the optimization process. One approach that used parametric modelling and optimisation of energy performance for hundreds of thousands of solutions in the cloud is shown in [78].

Independently from hardware, ray tracing solutions have recently started to implement progressive rendering techniques [79]. Over the years many different methods emerged to follow this concept based on interactive path tracing [80] [81]. The great benefit of this approach is that simulation can start showing rough results immediately in real time while accuracy increases over time. Simulation can be concluded by reaching previously set noise or time threshold, or it is up to the user to decide when to end the process. Recent development in progressive rendering for improved global illumination shows great improvement in speed [82].

4.5. Spectral rendering

Although a light spectrum covers huge range of wavelengths, particular interest for this research represents parts of the spectrum with a wavelength ranging from 280 to 1800nm: Near Ultraviolet (NUV), Visible (VIS) and Near Infrared (NIR). This range almost matches with the solar radiation spectrum AM1 (280-2500nm) that represents the standard for testing PV cells and modules, as all of the PV cells spectral response curves fit within these boundaries. However, common light model used for daylighting and visualization purposes covers only VIS part of the spectrum (380-700nm), neglecting light wave properties and NIR, NUV spectral part. This can cause inaccuracies, particularly when calculating irradiance values on surfaces integrating over only VIS spectrum, while only approximating NIR and NUV parts. PV output of the cells with significant spectral response in this part, such as crystalline Silicon (c-Si) or multi-junction, can be underestimated. Moreover, due to the huge computational expense at the time they were developed and in order to reduce the time required to create an image, daylighting and visualization tools further approximated handling of the visible spectrum information into tristimulus values RGB (Red, Green and Blue channels) [83].

RGB colour model is highly hardware dependent as it was designed for displaying images on screens. This model alone, neither other models such as CMYK, HSV or hardware independent CIE XYZ, is not suitable for accurate colour representation in rendering [84] due to the limitation of luminance and chromaticity output displays. RGB model neglects a number of phenomena important for truthfully accurate visualisation and simulation, like metamerism, wavelength dependent coloured scattering, dispersion, polarisation, fluorescence or spectrally selective absorption in participating media. Metamerism can cause the apparent colour of an object to vary significantly under different illumination spectrum. Furthermore, if renderer uses RGB model during calculation phase, results are produced with a shifted color space [85]. Same paper proposed a simulation alternative for improving physical accuracy of trichromatic coding schemes by combining a spectral rendering method with RADIANCE. They proposed N-step method where the solar spectrum is separated into N consecutive wavebands that form N channels used in simulation, rather than the standard three channels (RGB). Paper demonstrated that in order to achieve higher luminance accuracy levels of 5-6%, in comparison to nearly 20% with RGB models, spectral rendering is required. They found that 9-step is a reasonable approximation of the visible spectrum that produces accurately both luminance and color. Furthermore, all calculations are hardware-independent and conversion from XYZ to RGB space takes place only to actually displaying an image.

Considering PV material characteristics and especially semi-transparent PVs, it is important to take into account light transport in participating or volumetric media (defined in CG as absorbing homogeneous material) that follows Beer-Lambert's law and can also have wavelength-dependent scattering distributions [86]. It is usually calculated in a biased way, but there is an unbiased method as well [87]. A new efficient method to model complex lighting in participating media use Progressive Photon Beams (PPB) is presented by [88]. Absorbing only some fraction of radiant energy per unit length can result in distance-dependent spectral colour shifts. Consequently, light spectral power on the outer side will be modified compared to the incident one. Since PV cell can be considered as this type of media, where wavelength-dependent absorption is crucial for determining electricity yield from External Quantum Efficiency (EQE) and Internal Quantum Efficiency (IQE), spectral rendering embodies preferable choice. Particularly, in a case of semi-transparent and/or colored BIPV cells such as Dye-Sensitized Solar Cells (DSSC), or electrochromic glazing, color of the dyes in BIPV or chemicals in electrochromic glazing can shift light spectral power causing great offset in Color Rendering Index (CRI) of the indoor spaces [89].

Regarding thin films, highly nonlinear and wavelength and angle dependent refractive index of physically-based reflectance models, described by Snell's law and Fresnel formulas, can have a quite strong influence on the dispersion of the reflected and transmitted light on an interface, producing saturated colours from unsaturated ones. Research by Tandianus et al. presents an efficient way to compute spectral caustic rendering of a homogeneous caustic object based on wavelength clustering and eye sensitivity [90]. In addition, it can be essential for simulating micro or nano-sized antireflective coatings used in Low-e glazing or as a top layer in BIPV. This is the strongest wavelength-dependent effect and also the hardest to handle properly since it results in a direct dependence of ray direction on wavelength [91]. Low-e glazing, despite excellent solar heat gain performance, have a side effect evident as urban light pollution. Due to the spectral selectivity, especially in IR part of the spectrum, these types of glazing almost completely reflect IR rays toward urban surrounding causing excess radiation and increasing the effect of urban heat islands. Furthermore, if building shape contains concave shapes as in cases of skyscrapers so-called "Valkie-Talkie" in London and Hotel Verdara in Las Vegas, consequences may be fatal. Concave building shape of "Valkie-Talkie" produced concentrated light beam, also called "Death Ray", causing a light spot with about 10 times more intensity than average and temperatures exceeding 100°C [92]. Therefore, spectral rendering such as one proposed by [93] represents the only way to directly handle full spectral information during rendering, accurately perform simulations, colour rendering

results [94] [95] and estimate impact and light pollution that these types of glazing can produce to the environment. Radiant flux integral should be calculated from full spectral data, while tri-chromatic linear model is all that is needed only for the perceptual representation of a colour, where the last phase should convert spectral to RGB values for an image to be represented on an RGB monitor. However, despite promising trials to account for some of this spectral effects in three-component light models optimised for rendering [96], RGB model has never been designed nor ever be able to perfectly simulate spectral light phenomena and produce highly accurate results.

Spectral rendering can be also very valuable in emerging frameworks for evaluating non-visual effects of daylighting on human comfort, metabolism, health, well-being and productivity , especially concerning human circadian rhythm [97] [98] [99]. Inanici et al. [100] used previously described multi-spectral N-step method based on Radiance to demonstrate its ability and benefit for calculating circadian daylight performance.

Considering the computational power, when it was proposed more than 20 years ago, spectral rendering was overkill even for the most powerful systems, and meanwhile RGB has become a standard light model for rendering. However, with the enormous increase in the available computational power since then and further improvements and optimisation of the original method [101] [102], the additional computational expense of a full spectral simulation in comparison with an RGB model is almost negligible. As also noted in [17] spectral rendering is a promising development for future study of special coating and/or glazing materials widely used in solar architecture. Therefore, it can be concluded that the spectral rendering has become a reasonable and necessary step forward in visualisation, daylighting and BIPV simulation.

4.6. Types of simulations/analyses

The versatility of the physically based approach has found support in both CG art field (rendering) and architectural/building/lighting engineering field (daylighting design) from the early years of Radiance development. At that point in time, it represented a significant breakthrough, especially for the daylighting design after its numerous validations [43] [103] [104] [105]. Later improvements have been made to allow annual and climate based daylighting modelling using daylighting coefficients or sky mixing methods. Daylighting coefficients methods is originally proposed by Tregenza and Waters [106], and implemented by Reinhart and Henkel into Radiance as a DAYSIM extension [2]. Sky mixing methods interpolate values under a range of skies from clear to overcast for different points in time in a year. Support for the simulation of CFS and dynamic shading in form of three-phase and five-phase methods that use Bidirectional Scattering Distribution Function (BSDF) xml file [107] has also been implemented and validated recently [108][109]. Nevertheless, due to the computational time needed to calculate all of the points in time steps during the whole year, these methods implement point grids to collect illuminance data. This was a necessary approximation back then when accessible computer power was very low comparing to those nowadays. Since some current solutions in CGI already works in real-time, future directions will, therefore, increase the resolution of these grids and calculate annual daylight metrics as an image, being able to take into account also qualitative, visual and non-visual aspects of daylight.

Radiance engine's lack of appropriate GUI has limited its wider acceptance, especially among end-users and very vibrant and progressive CGI community. GUI applications that use Radiance engine rarely implement most of its features. Despite being designed for both qualitative and quantitative analyses, over the years its relevance in visualisation field has been constantly decreasing and eventually being overtaken by the majority of CG rendering tools available nowadays. Nevertheless, it is still considered a state-of-the-art method for daylighting simulation and most of the available daylighting tools use it as a ray-tracing engine. On the other hand, the majority of the visualization tools almost completely abandoned quantitative aspects of the simulations including daylighting and put a focus only on a visualisation part. Yet, according to trends, majority of tools that aim for physically based approach would sooner or later strive to unite artistic and scientific needs into versatile cross-industry packages, as it has already happened in automotive and aerospace industries and their cutting edge software like SPEOS, VRED etc.. Dubois and Horvat [17] also recognized that this is certainly an area which needs much development in the future. It is just a question of time before this approach becomes common in architecture/building industry.

Radiance pace in this development comparing to the other visualisation and gaming tools is very slow. It is likely that integration of Radiance concepts regarding annual daylighting with other advanced rendering tools and engines into hybrid approach will represent a step forward in the future solar design and particularly daylighting and BIPV design and simulation. Methods such as Accelerad [110] that extend Radiance classic engine to work on GPU with Nvidia Optix engine replacing traditional Radiance rtrace, or Photon Mapping [48] with its EvalDRCtool for the annual characterization of DRS [111] that adds bi-directional capabilities, will, hopefully soon, bring daylighting simulation necessary improvements.

Lastly, one of the promising approaches uses Precomputed Light Transport (PLT) for rendering complex scenes with a full indirect illumination in real-time and the ability to dynamically control local lights and viewing directions [112]. The approach uses radiance regression function to train the neural network in pre-computation phase to allow real-time rendering of the indirect illumination of the whole scene under different lighting and viewing conditions. The system focuses on achieving real-time rendering without sacrificing any global illumination effects resulting in high accuracy. However, the system still needs reasonable time for pre-computation phase, but authors claim that this can be reduced significantly. This could open up new real-time approaches to the annual daylight modelling.

4.7. Simulations' representation

Radiance engine has been designed as an extendable collection of modules/executables for UNIX without GUI allowing it to grow gradually by including many interesting concepts over time. Its robust light transport model supports calculation and storing colours as RGB values and illuminance as radiance floating point values. This approach is extremely important for later extraction of various types of analysis out of a single simulation run. In this way, many various modules have appeared over the years to interpret simulation results. This research will consider analyses that can be generally divided into several groups: qualitative – visualisation/rendering and human vision, and quantitative - photometric (illuminance/luminance), radiometric (irradiation/radiation) and colorimetric. Color information for the purposes of visualization can be extracted from a high-dynamic range images in floating-point 32-bit format to be represent in 8-bit mode, suitable for displaying images on screens. In case of high contrast dynamic range of the scene, tonal-mapping module such as Radiance pcond compresses pixel values from very dark to very bright areas using variety of mathematical techniques to determine appropriate exposure. It can simulate effects such as veiling glare, loss of focus and color sensitivity in order to evoke visual perception of the human eye in photopic, mesotopic and scotopic conditions.

On the other hand, modules for photometric and radiometric analyses neglect colour information, and extract only RGB intensities per channel, integrates and convert these values to radiometric and photometric quantities, in desired units. Due to the high dynamic range of these images and colour independence, these analyses are shown as false-color images. Although very basic, but very important option from the scientific and engineering point of view for quantity and quality of light/daylight and irradiance/temperature for BIPV, this option is neglected by many CG visualisation tools. However, some visualisation tools implement this option within their frame-buffer channels also called render passes/channels. As this type of visualization tools are used by architect more often than daylighting tools, the integration of quantitative analyses in the design process could be much easier if approached within visualization tools.

Most of the 3D visualisation software support high-dynamic range output of illuminance values via lightmaps or in other words illuminance values baked to a UV texture. These maps can then be converted to irradiance ones and integrated over the surface area to obtain a unique value for the purposes of PV assessment. In addition, lightmaps can be a great way to evaluate disposition and homogeneity of the illumination on the surface. Lightmaps creation is not dependent on light transport models and techniques. In addition to lightmaps, another approach in form of interactive lighting analysis grids was proposed by LightWorks and their iRay+ tool. These grids can be exported either in text format or presented as texture displays and shown directly within 3D environment. This method allows architects to explore lighting levels on a range of lighting grids through a model visually.

As already discussed in spectral simulation part, accuracy of photometric, radiometric and colorimetric analyses could be improved if the calculation model and storing data is spectral-based, rather than RGB. RGB model should be used only to extract color information for displaying final images.

4.8. Light sources

4.8.1. Natural

Analytical sky models are used for parametrically describing complex sky luminance distribution as more simple sky conditions. An analytical formula able to describe general luminance sky distribution was originally proposed by Perez et al. [113], commonly known as Perez All Weather Sky model. Slightly modified version of this formula, with tabulated parameters, was adopted by the International Commission on Illumination (CIE) and International Organization for Standardization (ISO) to create a joined standard [114] by refining all previous standards. It collected 16 different sky models describing luminance distribution for different atmospheric conditions, including models for overcast skies developed by Moon and Spencer [115], varying from clear sky to overcast with different luminance turbidity. Standardised sky luminance distributions are very important for daylighting analysis and comparative evaluation of alternative daylighting design options either through

computer-based simulations or through physical model testing in sky simulation facilities that can accurately reproduce these skies. For the purposes of daylight simulations, Radiance extension utility gendaylit implements these models. The most commonly used are CIE clear and overcast skies, while Perez All Weather model provide increased accuracy in absolute results. Limitation of these models from the BIPV simulation point of view is that they describe only the luminance distribution and neglect color as well as spectral (wavelength) information. Furthermore, these analytical models of sky luminance distribution deal only with the sky dome's appearance and exclude the solar disc. Therefore, they cannot be directly implemented for renderings without adjustments, but they are still used as a standard for daylighting simulations to provide illuminance values. Nevertheless, some of the rendering engines like Mentalray and Vray offer CIE and Perez sky definitions. Later developments were focused to account for physically based coloured skylight models, that are directly useful for rendering purposes - single scattering model [116], multiple scattering model [117]. Preetham et al. [118] developed a model based on the Perez All Weather model and Nishita model, that analytically solve sky luminance distribution. This model currently represents the de facto standard analytical model of coloured sky-dome radiance.

In their review, Zotti et al. [16] carried out experimental validation of Preetham and CIE models and pointed out on some issues of Preetham model, particularly in low sun position, suggesting improvements using spherical harmonics as proposed by [119]. Preetham et al. later improved this model by employing a separate analytical formula for adding a solar emitter of appropriate radiant intensity to account these issues. Although it produces sensible results, it still suffers from a range of numerical and accuracy-related problems. Bruneton and Neyret [120] presented an accurate method to simulate the skylight in real time that takes into account many effects of the light scattering such as Rayleigh and Mie multiple scattering, the daylight and twilight sky colour and aerial perspective. Hosek and Wilkie [121] [122] [123] went further in improving Preetham model developing separate fitting for each waveband by using look-up tables, accounting also for ground albedo and polarisation, resulting in higher level of precision and realism especially during sunsets and high atmospheric turbidity setups. Later, they improved their model and implemented a precise solar-Radiance function for direct solar radiation that exactly matches previous skylight model and produces reasonably accurate results [124]. Comparison between these two models made by Kol [121] showed that Hosek-Wilkie generally outperforms the Preetham model in terms of result accuracy, but it is 30% slower than the Preetham model simulation due to the searching of a look-up table. Although developed very recently, Hosek-Wilkie model has already been implemented in some tools like Luxrender, Corona, Cycles, Arnold, NOX, Mitsuba and Vray. It will certainly replace Preetham as a standard model.

When considering capturing of a spectral sky radiance distribution, which provides both spectral and spatial information about the radiation field, Pissulla et al. presented a methodology and calibration procedures for five instruments capable of making such measurements [125]. Four of these instruments were based on double monochromators scannng each wavelength in turn, and one was based on a single monochromator with a charged coupled device (CCD) allowing the recording of all wavelengths simultaneously. Measured results deviated from 3% to 35% due to the uncertainties arising from different calibration procedures and input optics with different FOV. Similarly to their, Tohsing et al. created their own hemispherical sky imager (HSI) made of commercial compact CCD camera equipped with a fish-eye lens to capture spectral sky radiance distribution from all-sky images for the complete spectrum in the visible part (380–760 nm). They used non-linear regression technique to obtain a spectral sky radiance from RGB values with a deviation of less than 20 % for all sky conditions comparing to the measured radiance distributions obtained by a CCD spectroradiometer [126]. Another approach that involves capturing high dynamic, spectral, and polarized natural light environment is shown in [127].

The most recent and comprehensive review and framework for an experimental comparison study of solar and skydome illumination is presented by Kider et al. [128]. They compared several state-of-the-art solar/sky model and indicated their strengths and weaknesses, and presented deviations from measured results. They concluded that brute-force models like Nishita and Haber are excellent in accounting for the direct solar and scattering parameters but they are not suited for time efficiency and real-time graphics since brute force path tracing is considerably slower than pre-catching methods. On the contrary, Preetham, Hosek and Bruneton path-traced real-time models produce very fast results but at the expense of accuracy in favour of speed. These balanced approaches should represent ultimate user choice for the majority of tasks.

In addition, Kider et al. proposed their own spectral data-driven sky model built from the spectrophotometer measured data. This illumination model can find its application in rendering, daylighting, or thermal studies since the illumination information spans across a spectral range of 350nm to 2500nm, as opposed to RGB trichromatic visible spectrum of a HDR image. This would have enormous benefits to the wide community of both academia and practitioners in producing more physically accurate simulations. Unfortunately, the model is still not available for the public but its release is expected soon. Furthermore, since both complex analytical and

data-driven models are costly to compute interactively, Satilmis et al. proposed machine learning approach to compactly represents sky illumination from both existing analytic sky models and captured environment maps [129]. The model is proved practical as a generic approach for both offline and real-time applications.

Considering commercially and publicly available methods, currently the most popular method for representing luminance sky distribution in CGI remains HDRIs. They are mostly used for artistic image-based lighting visualisations due to the high realism, but they can be used also for environmental validation purposes to represent real sky luminance distribution for daylighting purposes [130] [131] [132] and semi-transparent BIPV [133].

In conclusion, since spectral properties are very important for BIPV simulation latter models based on Preetham are more suitable than classical Perez model, while improved version of Hosek-Wilkie model represents currently the most suitable choice for accurate color representation and visualization, as well as simulation of BIPV and daylighting within 3d CAD environment.

4.8.2. Artificial

Light distribution from the artificial light sources is defined by the spatial luminous intensity data presented in photometric files. There are two photometric data files types currently used. First, called IES, and most used one is proposed in 1986, and later updated in 1995 and 2002, by the Illuminating Engineering Society of North America (IESNA) in the standard LM-63-86 on "IES Recommended Standard File Format for Electronic Transfer of Photometric Data."[134]. Another format is EULUMDAT (also known as LDT, after its file extension) and it is mostly used in Europe, but it has remained largely unchanged since its introduction in 1990.

4.9. Simulation scale

4.9.1. PV cell and material scale

Our present understanding of the light behaviour is based on hierarchical models where lower levels are based on simplification assumptions. Quantum electrodynamics or quantum optics presents the de facto highest level of this hierarchy, followed by electromagnetic and wave optics. Optical modelling and simulation for multi-layered photovoltaic devices, such as thin-film, generally uses a wave-based light model that can account for rough interfaces. As rough interfaces presents one of the most powerful methods for improving cell efficiency by increasing light path length inside the active medium, estimating and determining the exact amount of light absorption in component layers, comprising thin film solar cells, is of the utmost importance when studying the cell efficiency in relation to the cell structure and the optical characteristics of materials [135].

However, most models of light trapping are still designed to account only for optical effects, although modelling both the electronic and optic characteristic of advanced photovoltaic devices is desirable in order to account for effects such as carrier recombination to calculate device performance more precisely. The level of approximation greatly depends on the scale of the structure being simulated. If this dimension is much larger than the wavelength of light, most basic geometric (or ray) optic model of light provides a reasonable approximation. This model of light can be represented by intensity or photon flux where light propagation assumes that photons can be emitted, reflected, transmitted and absorbed according to the Snell's law. However, this model makes a number of simplifying assumptions regarding the light behaviour that limits the types of phenomena that can be simulated. Effects such as diffraction and interference (wave optics), polarisation and dispersion (electromagnetic optics), and fluorescence and phosphorescence (quantum optics) are completely neglected. Nevertheless, this model is still able to properly simulate a wide range of physical phenomena. Although wave models are mostly used to simulate PV under direct sunlight source they not capable enough to simulate complex shapes under diffuse sunlight [136]. On the contrary, geometric optics model represented by ray tracing approach is more flexible at simulating these geometries under both direct and diffuse sunlight. Optical simulations based on geometrical ray tracing is usually based on the indirect method of totally flat surfaces and interfaces, determining the energy absorbed by combining the absorption coefficient and the incoming light energy which was obtained by calculating reflectance and transmittance [137]. Successful implementations of geometrical optic model for simulating PV yield include [138] [139] [140] [141] [142] [143] [144]. Most of them used in-house software tools and specific models to simulate different PV cell types. On the contrary, implementations of ray tracing tools from other disciplines are presented by Kerrouche et al. [136] who performed experimental validation of commercially available SPEOS Optisworks 3D optical ray-tracing simulations for luminescent solar concentrators BIPV thus achieving good of <7%. This software is also used in a simulation of a novel non-imaging stationary window integrated 3-D solar concentrator (SEH) developed by Sellami and Mallick [145]. Another commercially available ray tracing software for estimating PV yield of complex systems are among others ASAP, TracePRO and Raywiz-SOLAR. Latter is used by [135] to develop a new direct method based on Monte-Carlo non-sequential ray tracing techniques that is able to calculate accurate

amount of absorbed energy in the individual layer with rough surface of BSDF characteristics regardless of coherent and/or incoherent light inside the medium. This is proved very effective in analyzing complex geometries. Hybrid models based on the combination of incoherent geometric optics and coherent wave optics analysis, employed independently to simulate light propagation through the thick front textured component and the bottom flat thin-film component of the device are respectively demonstrated in [146].

4.9.2. BIPV facade module to building scale

All above-mentioned higher light models are suitable only for PV simulation on a cell level. Due to the scale of the objects and structures in regular scenes in computer graphics, the lowest ray optic model is predominantly used for rendering and visualisation. From a mathematical perspective, ray optics is the limit of wave optics when the wavelength is infinitesimally small [147]. Connecting these techniques with ones designed for building or urban level cannot be done without significant approximation in order to estimate both daylighting of indoor spaces and electricity yield of the BIPV cells and modules in either unobstructed or complex urban environments. Yet, this connection is crucial for designing BIPV and targeting Zero Energy Building (ZEB) goals.

There are several methods showing how this could be achieved and general classification can be made concerning dimensionality of space. Higher in the hierarchy is the three-dimensional (3D) approach by using BSDF [148]. It defines how light is scattered by a surface and it can be described as a black box where the inputs are represented by any two angles (one for incident ray and the second one for the outgoing (reflected or transmitted) ray) at a given point of the surface. The output of this function is the value defining the ratio between the incoming and the outgoing light energy for the given couple of angles. Therefore, BSDF is a superset and the generalisation of the Bidirectional Reflectance Distribution Function (BRDF) and Bidirectional Transmission Distribution Function (BTDF) [149].

BSDF is generally used to define light scattering through Complex Fenestration Systems (CFS). CFS refers to any window product that incorporates a non-clear (non-specular) layer in the glazing assembly or in its attachments (e.g., shadings). CFS are particularly interesting for Daylighting field as their angle-dependent properties are exploited to improve daylighting in indoor environments. Their optical properties are often defined by discretized BSDF models that use subdivisions to form a BSDF matrix. The most used and the most simple is the Klems angle basis matrix based on division model proposed by Tregenza [150] containing 145 patches. Models that are more precise include 2x (580 patches), 4x (2320 patches) and 6x - Reinhard model (5185 patches) subdivision of the Klems model. The latter one is used for defining direct sunlight in daylighting simulations, particularly Radiance five-phase simulation [108]. One of the very few advanced approaches to implementing Radiance BSDF for complex BIPV simulation is proposed by Sprenger [151]. It is based on Radiance engine and BSDF approach to calculate irradiances on the top layer, while the procedure is followed by a 1d approach that includes additional software for semiconductor analyses, in this case ASA [152], in order to perform the full simulation. This methodology presents one of the best ways to account for simulation of complex BIPV but it still does not have GUI, it depends on custom scripts and procedures and it is not yet suited for the wide usage. It will be very interesting to see how this model will evolve and if it will succeed to become ready to use tool for a broader range of users.

BSDF model can be very versatile and include different values such as solar heat gain (g-value) to follow the same procedure. It is usually implemented in coupled simulation to estimate thermal properties of CFS in whole building simulations [153] [154] [63] [155]. This kind of angle-dependent approach is the most desirable method to simulate BIPV electricity yield, as it is general and robust and can account for anisotropic materials.

However, most of PV tools do not use BSDF approach but some simplified models. Calculation of irradiance on PV modules, used in common PV simulation tools, is usually approximated by means of calculating global irradiance on the PV surface as a Plane of Array (POA) value. POA represents a sum of separate irradiance contributions from POA beam component, POA sky-diffuse component and POA ground-reflected component (albedo).

POA beam component is the most important of them as it represents irradiation contribution from the sun. It is an analogue to the direct illumination component in 3D visualisation tools. As all testing of modules predicts calculations of PV performance under light sources perpendicular to the PV surface, this component implements Angle Of Incidence (AOI) correction to adjust the Direct Normal Irradiance (DNI) for incidence angles greater than 50 degrees [156]. 2D function Incidence Angle Modifier (IAM) is used to define optical losses, due to angle dependent reflections, from arbitrary optical surfaces of the PV module top layers. IAM value is usually calculated using analytical IAM models such as physical [157], Souka and Safwat [158] or ASHRAE [159], Martin and Ruiz [160] [161] [162], and Sandia [163]. Additionally, IAM of complex surfaces can be calculated by optical software such as TracePro and Zemax to characterise optical properties of the top layer of the PV cell as a 2D function of the incidence angle of the light source [164] and finally be provided as an output for PV

software such as PVsyst [165]. In this way, optical simulation is separated from electricity yield simulation. This approximation implies that surfaces have only isotropic properties. For calculating IAM and consequently POA beam component PV tools compare solar azimuth and zenith angles, with the PV module azimuth and tilt angles respectively.

POA sky-diffuse component accounts for a diffuse radiation from the sky dome and is usually described by several models ordered by level of accuracy: Isotropic, Simple Sandia, Hay and Davies, Reindl and Perez. All except Perez calculate isotropic, circumsolar, and horizon components separately, while Perez model is based on empirical coefficients for each of them [166] [167] [168]. Since sky models based on Perez represents de facto in 3D visualisation tools and only an advanced option in PV simulation tools, it is likely that all 3D visualisation packages will outperform PV simulation tools in terms of irradiance and sky model accuracy. Moreover, PV tools calculate only one value per module while 3D visualisation tools can perform even very precise irradiance distribution on whole PV surfaces and account for irradiance homogeneity and partial shadowing.

Contrary to advanced ray tracing approaches to calculate irradiance distribution on surfaces, most of the PV simulation tools do not support complex lighting conditions and near shading caused by surrounding, as they are mainly developed for stand-alone PV modules in energy plants. However, some of them like PVsyst still can be used for roof-mounted PV that uses shading factor to account for near shading effect [169]. This is a highly complex procedure relying on many approximations, it is not physically based and it cannot model specular near field objects. This can have negligible energy related consequences for roof-mounted PV but significant for BIPV in urban conditions. For the general purpose of the BIPV, this approximated model is outdated, and ray tracing approach should be used instead. One approach that partially exploits this method is shown in [151]. Technique considers complex shading environment to address direct and diffuse irradiation on the PV surface separately and then further approximated by 1D model to estimate PV electricity yield. This process is also limited by the Radiance inability to model multi-layered material that includes any arbitrary layer properties including dielectric, translucent, thin-film and rough surfaces. This feature is extremely important for simulating full-layered BIPV and possibly calculates angle-dependent irradiance values only on active PV layer.

POA ground-reflected component is a function of Global Horizontal Irradiance (GHI), reflectivity of the ground surface (albedo) and the tilt angle of the surface. Again, a huge approximation is reasonable in open spaces as in the case of PV plants but highly inaccurate in urban areas. Similarly to the previous component, 3D packages using advanced light transport models that can model urban environment should outperform PV tools in terms of accuracy.

In order to avoid approximation in calculating effective irradiance on PV layer, some advanced and comprehensive frameworks for rendering layered materials may be very useful for the needs of BIPV. Instead of calculating irradiance on the top layer and converting it to effective irradiance on PV layer, layered approach is able to calculate effective irradiance directly. Approach is based on microfacet models to perform the physically based calculation of light transport through an arbitrary stack of arbitrary BSDF surface properties and thicknesses including thin films [170] and [171]. Render engines such as Unity, Cycles, Vray and Arnold alShader model uses über-shader principles to combine multiple microfacet surfaces in simplified and straightforward manner while preserving energy conservation principles [172]. This concept has also been tested successfully in real-time rendering [173]. Improved version, that includes discrete stochastic for random spatial variation of BRDF, is presented recently [174]. In order to solve antialiasing of surfaces using high-level of details using microfacet models at all scales Dupuy et al. proposed Linear Efficient Antialiased Displacement and Reflectance (LEADR) Mapping [175]. Multi-scale approach of rendering composite materials, whose morphological structures are defined at several embedded scales, using homogenization process was shown in [176]. The same tool – Ocean is even capable to calculate absorption in form of EQE of specific material in layered structure, which could find application in complex BIPV modules and novel PV cell technologies.

However, most of CG software used for daylighting and rendering purposes do not support materials defined by complete BSDF stack model due to the increase in calculation time. Instead, they mostly use only simplified BRDF models while BTDF part is considered as caustics and it is only turned on in some special cases. Some of the most known BRDF approximated (shading) models used in CGI are: Lambertian (perfectly diffuse BRDF constant), Phong, Blinn–Phong, Ward, Oren–Nayar, etc. Most of them represent an approximation of anisotropic model (3D) into isotropic two-dimensional (2D) BSDF model. In that way, they are not completely accurate but they try to define most basic types of reflections computationally cheap. On the other hand, physically-based BRDF models that follow positivity, Helmholtz reciprocity and conserving energy principles [177] represents a very active area of research and recently some CGI tools such as Arnold and Maxwell start to implement them as standard features to achieve a high level of accuracy and visual effect. One of the most extensive BRDF reports in the past that used data-driven reflectance model [178] to measure 100 different materials. However, this approach used custom-made measurement equipment and further measurements of additional materials were not easily achievable. Main issues that limit the effective use and exchange of material models was presented in

[179]. In the past years, NVIDIA has proposed a standard called Material Definition Language (MDL) that aims to overcome interoperability issues and define physically based BRDF functions, independently of platform, that should provide easy conversion of materials among rendering tools. Materials can be also be physically measured via measurement devices from X-Rite, Radiant Vision Systems, Light Tec or Speos, or via companies like Vray and MegaSets that offer physically accurate measurements of materials for a fee.

4.9.3. Building to urban scale

Simulating light on building and urban level brings more approximation to the light transport models. Regarding BIPV on this scale, the most basic model that takes into account only global irradiation values on the surfaces and calculates PV electricity yield is often used. Since irradiance directly influences the temperature and electrical performance of a PV cell, this review gives particular interest to address how these irradiance values can be obtained in various 3d modelling and visualisation environments to be used to simulate PV energy yield on any spatial distribution of irradiance in any 3D scenario. This can be described generally as a one-dimensional (1D) approach.

Three models are commonly used to predict photovoltaic module performance as a function of irradiance intensity: power temperature coefficient model [180], (2) the PVFORM model [181], and (3) the bilinear interpolation model [182]. Method (1), also called PVWatts [183], calculate maximum power as a function of only temperature and POA irradiance for POA > 125 W/m2. The formula is derived from measurements data of the operational performance of grid-connected PV illuminated under one sun intensity value (1000W/m^2), key reference value used in a Standard Test Conditions for PV/BIPV [184] [185] [186], although variants in light intensity from 100 to 1100 W/m^2 under temperature range 15-75°C are also applied [187]. Consequently, method (1) is therefore not directly applicable to the low levels of effective irradiance. Marion [188] [189] suggested improved version of the PVWatts model in order to account for errors due to the non-linear decrease of efficiency at lower irradiance levels. Other two methods are able to account this issue but include others such as technology-specific corrections and calibration and address mostly PV based on c-Si. [190]. Empirical models such as Sandia PV Array Performance Model (SAPM) [163] and Loss Factors Model (LFM) [191] represent technology performance differences and their changes over time better. LFM is more advanced as it takes into account five physically significant and independent normalized "loss factors" as well as spectral and temperature corrections to estimate Final Energy Yield (YF) or Performance Ratio (PR) for most PV module technologies (c-Si, HIT, a-Si, CIGS, CdTe and a-Si/uc-Si). Due to their not optimal placement represented in various types of inclination and orientation, irradiance conditions of solar cell efficiency of BIPV in the range of 100 -1500 W/m^2 are of particular interest for this research.

Many researches has been carried out to investigate the behaviour of the PV cells under low light conditions, such as for c-Si[192], a-Si and CIGS [193] and other cell materials [194][195][196]. Stamenic et al. demonstrated the influence of low light conditions in the simulation of (BIPV) systems [197]. It is shown that the cumulative impact on PV module performance can decrease by 30% in module efficiency from 1000 to 200 W/m^2, whereas in some latitudes this drop can go as high as 57% [198]. For this behaviour, non-ideal photovoltaic cell characteristics at low irradiance are most responsible factor, while the angle of incidence and spectral changes only account for up to 15%. Due to the difference in PV energy yield performances among different cell types and their constant increase in efficiency, irradiance values should be always used as a reference while functions to convert it into Maximum Power Output (MPO) should be applied always with most recent updates of cell efficiencies, or preferably with data provided by manufacturers for specific BIPV product.

One of the earliest applications of daylighting/visualisation software for estimating PV energy output can be found in [199]. In this case, Radiance ray tracing is used to produce irradiation distributions on the PV panel arrays in an urban environment. However, this approach was not integrated into CAD environment and therefore not very useful from architects' point of view. Furthermore, slow computation time caused by old inefficient methods of ray tracing approach caused delays and discontinuity to the design process [200] [201]. To address this issue, rasterization has found to be used in a real-time manner, simulating irradiance for PV products and BIPV in a virtual reality environment [202]. Veldhuis et al. used custom-made tool VR4PV to achieve flawless design process with a real-time preview and processing time as a factor 0.01 compared with common ray tracing algorithms to estimate performances in terms of irradiance, shading, temperature, and the electrical yield of the PV cell, representing valuable feedback for designers. However, rasterization technique applied, by default lacks the possibility to account for complex reflections and transparent materials, particularly important for daylighting scenarios including complex BIPV. Another time-efficient design method to assess irradiance levels on the PV cells in an arbitrary geometry by means of ambient occlusion is demonstrated in a 3D-PV tool [203].

What is common for abovementioned methods, based on predicting PV electricity yield from irradiance values, is that measurements are usually taken as a point-in-time or single measurements. However, for the BIPV energy output predictions, it is necessary to perform simulations on an annual basis. Robinson and Sone

proposed a method for Radiance, available as GenCumulativeSky, that takes a climate file as an input and generates a cumulative sky Radiance distribution. It may be described either in terms of a global Radiance distribution for a discretized sky vault, or a diffuse discretized Radiance distribution with either hourly or a statistical subset of suns, and produces annual irradiation images from a single simulation [204]. Method successfully combines advantages of alternatives approaches represented through a computational efficiency [205] and accuracy [206]. This approach has found particular application in estimating precisely annual solar irradiation on the building envelope and in urban context, useful for identifying areas with a good PV potential and areas with an excessive solar exposure (overheating) that should consider shading options for reducing solar penetration. Another very accurate method for predicting PV potential through irradiance on the surface is A360 rendering engine used in Autodesk Green Building Studio. This method is validated in NREL according to the standard calculation methods for POA irradiance[168][207]. Both engines present valuable tools for estimating BIPV potential that can compete with tools designed only for PV, while effectively and accurately accounts for shading and complex environments contrary to the standard POA methods.

Compagnon [208] went further than singular irradiance and proposed a method that evaluates several sustainability metrics (potential of the zone for active and passive solar heating, photovoltaic electricity production and daylighting) of urban massing models based on a cumulative incident global irradiation and illuminance reaching the buildings envelopes (facades and roofs). While very useful in the early design phase, this approach does not consider daylighting of indoor spaces. Therefore, [209] developed a methodology that translates outside hourly radiation data falling on facades into interior illuminance distributions to reduce computational effort. Although method is based on a significant simplification that eliminates direct radiation in the interior distribution, authors claim the new method produce hourly results with the reasonable precision of 7-18% for the interior illuminance and 3.8 – 10% for the climate based metrics while being up to 84 times faster than the standard Radiance/DAYSIM approach. ARCHSIM and umi, plugins for Grasshopper and Rhino, already implement this method and offer simple BIPV tool to estimate energy output.

Another efficient method is proposed by Jones and Greenberg [210]. They combined hardware pixel counting and B-spline surface interpolation to calculate the solar gain on architectural CAD models at any stage in the design. The method is designed as a pre-processor that feeds energy simulation tool EnergyPlus with the result. The method can simulate complex models without geometric simplifications or approximations that may cause loss of accuracy with no additional computational cost. This is proved very suitable for enabling performance informed decision-making in early design phase parametric exploration.

4.10. Integration and interoperability

Integration of solar design tools in CAD environment has evolved over the years and it can take different forms from full integration in 3D CAD environment up to a standalone tool. For understanding advantages of the new forms of integration it is needed to firstly explain their levels. The first method of integration, or lack of it, is the most basic level so-called parallel workflow where simulation tool differs from 3d modelling tool and the communication between them is conducted through the export of files from 3d tools and import into simulation tools. This approach still represents a common way, but it has numerous shortcomings as every change is manual and it is not possible to get feedback information. The new iteration has to be carried out in the same manner as the first one and there is no option for automatic optimisation. The more advanced level is the dynamic or live link workflow where two tools exist as standalone but simulation tool can be paired to read geometry information instantly and provide results for every design change without the need to export files. This is surely a preferable method but it greatly depends on the simulation speed. To avoid excessive computation, it is common to have only update button to run the simulation only when needed. Alternative ways are progressive calculation where result's quality improves over time or employment of cloud simulations that are able to calculate any scene in real time. Nevertheless, this is still a costly process to be implemented for design versioning and usually done only for the final calculation. Similar to this one in terms of the design process is the embedded workflow where simulation plugins or add-ons are integrated within 3D CAD environment. Differences can be noted in more flawless design workflow that is optimised for speed and interaction. Improved version of latter two is represented in design workflow that is supported by the optimisation algorithms and multi-solution comparison in either simplified manner or more advanced parametric workflow. Parametric-based tools are mostly integrated into Rhinoceros 3D and Grasshopper such as DIVA, Honeybee, Mr.Comfy, UMI, ARCHSIM, while Revit and Dynamo solutions keep pace and offer similar add-ons. However, more developments are needed to provide guided workflows more suited for designers and architects like goal-based methods in Lightsolve [211].

5. Part II – tables

Feature comparison matrix — PV software tools

Legend:
- ● standard feature
- ◐ tweaking possible
- ○ data not provided / not supported

▼ Polysun

Category	Feature	System Advisor Model	PVsyst	PV*SOL	Skelion	Solarius-PV	Polysun	CECPV Calculator	PVwatts	DDS-CAD PV▼	INSEL	PV Designer	PV F-CHART	SMA Off-Grid Configurator	SolarPro	Archelios	PV-DesignPro	RETScreen Plus	HOMER Pro	PVscout	HELIOS3D
light sources	natural - sun and sky (simplified/POA)	●	●	●		○	○	●		●	●		●	●	●	●		●		●	●
	natural - sun and sky (CIE/Perez)	●	●		●	○	○		●	●	●		●							●	
database	batteries				●	●	●				●	●						○	○		
	inverters database	●	●	●		●	●	●		●	●	●	●	●	●	●	●	○	○	●	●
	PV modules database	●	●	●		●	●	●		●	●	●	●	●	●	●	●	○	○	●	●
PV performance models	Sandia	●	●		○	○	○		○		○	○			○	●		○	○		
	CEC	●			○	○	●		○		○	○			○			○	○		
	one/two diode (equivalent circuit)	●	●	●		○	○	○	●	○	●		○	○	●	○		●	○	○	●
	PVFORM (PVWatts)	●			○	●			●	●		○	●	○		○			○	○	
simulations/ analyses	rendering/visualisation					●				●											
	BAPV/roof-mounted PV energy yield	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	◐
	LCOE/LCC/payback time	●	●	●	○	●				●		●	●		●	○			●	●	●
shading	simplified near-filed shading	○	●	●	●	●	●			●	○	●		○	●	●			○	●	●
PV technology	c-Si			●	●	●	●	●	●	●	●	●	●		●		●	●	●	●	●
	thin film			●		●	●			●	●	○				○		●	●	●	
	hybrid (HIT)			●		●	●			●		○			○	○				●	
	all technologies	●	●	●							○	●	○	○	●	○				●	○
design phase	conceptual/early phase		●	●					●											●	
	schematic	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●
	design development	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●
design workflow	real-time simulation/progressive				●																
	multiple solutions comparison	●			●						○	●		○		○	○	●	●	○	
	integrated optimisation	●		●							○	●		○		○	○	●	●	○	
	dynamic simulation (other renewables)	●				●	●			◐	○			○		○	○	●	●	○	
	3D environment		●	●		●				●	○	●		○	●	○				●	●
computation	CPU based	●	●	●	●	●	●	●		●	●	●	●	●	●		●	●	●	●	●
	GPU based																				
	multi-threading	○	○	○	○	○	○	○		○	○	○	○	○	○		○	○	○	○	○
	local network (multi-node)																				
	web/cloud			●	●		●		●		●					●				●	
	instancing (proxies)																				
system	graphical user-interface	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	open-source	●						●													
	Windows	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●
	Mac OSX	●		●	●		●														
	UNIX (Linux)			●																	
integration general	stand alone	●	●	●			●	●		●	●	●	●	●		●	●	●	●	●	
	3D plugin				●											●					
	CAAD/BIM integrated plugin					●				●					●						●
	(online/cloud/app) web based			●			●		●					●	●					●	
integration general 3D	Edificius					●															●
	DDS-CAD									●											
	Sketchup					●										●					
interoperability	CAD/BIM interoperability (IFC, IGES)				●					●	○	○						○			
	DDE (dynamic data exchange)				●					●											
	CAD interoperability (fbx, dwg, dxf, sat)		○	○	●	●				●	○	○	○		●	●	○			○	●
	BIM interoperability (IFC, IGES)									●											
pricing	freeware	●		●				●								●		●	●	●	
	free for educational/non comercial use																				
	educational/student discount					●													●		
	payware			●	●	●	●		●	●		●	●	●	●	●	●		●	●	
	flexible payment options (subscription)																		●		●
	bundled																				

Legend:

- ▼ Radiance
- ▽ DAYSIM
- ■ A360
- ◺ Nvidia Optix
- ◿ Nvidia IRay/Optix
- ☆ PHANIE
- ▲ EnergyPlus
- △ OpenStudio
- □ DOE

- ● standard feature
- ◉ tweaking possible
- ○ data not provided / not supported

		optical design/multiphysics													daylighting/whole building energy														urban	
		TracePro	Photopia	OpticStudio	ASAP	FRED	OptiCAD	LightTools	SPEOS, THEIA RT	Integra Lumicept	LucidShape	OSLO	OpTalX	COMSOL	TAS Engineering	OpenStudio	Sefaira	DesignBuilder	IES-VE	Green Building Studio	BSim	Honeybee	Mr. Comfy	COMFEN	ODS Studio	Vabi building performance	AECOsim Building Designer	ArchiWIZARD	ARCHSIM	umi - urban daylighting
light sources	natural - sun and sky (CIE/Perez)	●	●					○	●	○	○	○	○	○	●	●	●	●	●		●	●	●	●	●		●	●	●	●
	natural - sun and sky (Preenham)	◉	○	○	○	○		●	●	●		○		○	●	●	●	●		●			●			●		●	○		
	natural - sun and sky (Hosek-Wilkie)													○																	
	image-based (HDRI) lighting	◉	◉	○	○	○		○	●	●	●	○	○	○	●	○	○	○	●			○			●			●		○	
	artificial - IES/EULUMDAT (luminaires)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○	●	●	●			●			●					
geometry	solid (NURBS)	●	●	●	●	●	●	●	●	●	●	●	●	●																
	polygon mesh							●							●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
simulations/ analyses	rendering/visualisation	●	○	●	○	●	●	●	●	●			○	◉	●	◉	●	●			●					●			●	●	●
	photometric (illum.-lum.)	●	●	●	●	●	●	●	●	●	●	●	●	●											●			●		●	●
	radiometric (irrad.-rad.)	●	●	●	●	●	●	●	●	●	●	●	○	●											●			●		●	●
	colorimetric	●	○	●	●	●	●	●	●	●	○	○	○	○																	
	human vision	○	○	○	●	●	●	●	●	●	○	○	○	○																	
	daylighting (climate-based/annual)	◉	●	●	○	○		○	○	○	○	○	○		●	●	●	●	●	●	●	●	●	●	●				●	●	●
	daylighting (point-in-time)	●	●	○	○	○		●	●	●	●	○	○	◉	●	●	●	●	●	●	●	●	●	●	●			●	●	○	
	green certification report (LEED, etc.)														●	◉	●	●	●	●	◉	◉						●	○		
	BAPV/roof-mounted PV energy yield	●	◉	○	○	○		◉	●	●	◉	○	○	◉		●		●					◉	◉				◉	●		
	BIPV energy yield	●	◉	○	○	○		◉	●	●	◉	○	○	●				●					◉	◉				●			
	whole building energy														●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●
	glare								●	●	●				●	○	○	○			●	●	●	●	●	●					
	lighting	●	●	●	●	●			●	●	●	●	●	○				●	●		●	●	●	●	●	●	○				
	cost/LCC															○	◉	●	●								●				
	floating point images output	●	○	○	○	●	●	●	●	●	●	○	○	○		●						●				○		○		●	●
accuracy of calculation	unbiased (physically-based)	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●			●	●	●	●	●	○		○	○	●	●
	biased														●				◉									●	○	●	●
radiosity	radiosity														●				◉									●	○		
raytracing	forward (from light source)	●	●	●	●	●	●	●	●	●	●	●	●	●																	
	backward (from camera, sensor)	●						●	●	●	●				●	●	●	●	●			●	●	●	●	●	●	●	○	○	●
	bi-directional								●	●										●											
	ray paths preview	●	●	●	●	●	●	●	●	●	●	●	●	●																	
hybrid calculation	radiosity+raytracing														●				●												
	rasterization+raytracing																														
light spectrum	visible - RGB	●	●	●	●	●		●	●	●	●				●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	visible - spectral	●	●	●	●	●	●	●	●	●	●	●	●	●																	
	UV-VIS-IR - spectral	●	●	○	○	○	○	○	○	○	○	○	○	●																	
	polarisation	●	○	○	○	●	○	●	●	○	○	○	●	●																	
BSDF	BSDF (.xml)	●	●	◉	◉	◉	◉	●	●	●	●	○	○	○	◉		●	○			●	●	○	◉	●	○					
	Material Definition Language																														
	custom material BRDF	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○	○	○	○		●	○	●	●							
	basic materials BRDF	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○	●	●	●			○	○				
scale	urban								●	●					●	●	●	●			●			●			●		●	●	●
	building	◉	◉	◉	◉	◉			◉	●	●				●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●
	single room	●	●	●	●	●			●	●	●	◉			●	●	●	●	●	●	●	●	●	●	●	●					
	module (facade component)	●	●	●	●	●	●	●	●	●	●	●	●	●								●									
	cell	●	◉	◉	◉	◉	●	◉	◉	◉	◉	●	●	●																	
design phase	conceptual/early phase	◉	◉	◉	◉	◉		◉	◉	●				●		●	●	●		●	●	●	●	●			●		●	●	●
	schematic	●	●	●	●	●		●	●	●	●				●	●	●	●	●	●	●	●	●	●	●			●		●	●
	design development	●	●	●	●	●		●	●	●	●				●	●	●	●	●	●	●	●	●					●		●	●
design workflow	real-time simulation/progressive	●	●	●	●	●	○	○	●	○	●	○				●												●		●	
	multiple solutions comparison	●	●	●	●	●	○	○	○	○	○	○		●		●	●	●	●	○		◉	◉					●		◉	◉
	integrated optimisation	●	●	●	●	●	●	●	●	●	●	●		●	◉		●		◉			○	◉	◉				●		●	●
	parametric design (node based)	●	●	●	●	●	●	●	●	●	●	●	○	●			◉					●	●	●				●		●	●
computation	CPU based	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●			●	●	●	●			●		●	●
	GPU based								○	○	●																	○			
	multi-threading	●	●	●	●	●	●	●	●	●	●	○	○	●	●	●		●	●			●	○		●			○	○	○	○
	local network (multi-node)																														
	web/cloud														●	●		●	●									●			
system	graphical user-interface	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	open-source															●						●			●						
	Windows	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Mac OSX															●	●					●			●				●		
	UNIX (Linux)															●						●			●						

Legend:

Symbols (left):
- ▼ Radiance
- ▽ DAYSIM
- ■ A360
- ◣ Nvidia Optix
- ◺ Nvidia IRay/Optix
- ☆ PHANIE
- ▲ EnergyPlus
- △ OpenStudio
- □ DOE

Symbols (right):
- ◕ standard feature
- ⊘ tweaking possible
- ○ data not provided
- (blank) not supported

Column headers (software tools):
Radiance - classic · Radiance - DAYSIM · Radiance - photon map · Diva · DAYSIMpm · IDA ICE · SPOT · ReluxSuite / Pro · Accelerad · Geronimo · DIAL +Suite · su2ds · LightStanza · Light Studio · Rayfront · Lighting Analysis for Revit · Solar Analysis tool · VELUX Daylight Visualizer · AGi32 · ElumTools · Lightsolve · LightUpAnalytics · DIALux (4, evo) · LightCalc · CSTB D1 PHANIE-2010 · ecoBIM (TAS Engineering) · LD Assistant · Shadow Analysis · Chronolux · Ocean · BIM IQ

Category	Feature
light sources	natural - sun and sky (CIE/Perez)
	natural - sun and sky (Preenham)
	natural - sun and sky (Hosek-Wilkie)
	image-based (HDRI) lighting
	artificial - IES/EULUMDAT (luminaires)
geometry	solid (NURBS)
	polygon mesh
simulations/ analyses	rendering/visualisation
	photometric (illum.-lum.)
	radiometric (irrad.-rad.)
	colorimetric
	human vision
	daylighting (climate-based/annual)
	daylighting (point-in-time)
	green certification report (LEED, etc.)
	BAPV/roof-mounted PV energy yield
	BIPV energy yield
	whole building energy
	glare
	lighting
	cost/LCC
	floating point images output
accuracy of calculation	unbiased (physically-based)
	biased
radiosity	radiosity
raytracing	forward (from light source)
	backward (from camera, sensor)
	bi-directional
	ray paths preview
hybrid calculation	radiosity+raytracing
	rasterization+raytracing
light spectrum	visible - RGB
	visible - spectral
	UV-VIS-IR - spectral
	polarisation
BSDF	BSDF (.xml)
	Material Definition Language
	custom material BRDF
	basic materials BRDF
scale	urban
	building
	single room
	module (facade component)
	cell
design phase	conceptual/early phase
	schematic
	design development
design workflow	real-time simulation/progressive
	multiple solutions comparison
	integrated optimisation
	parametric design (node based)
computation	CPU based
	GPU based
	multi-threading
	local network (multi-node)
	web/cloud
system	graphical user-interface
	open-source
	Windows
	Mac OSX
	UNIX (Linux)

Legend

- ▼ Cinema 4D render
- ▽ Maxwell Render
- ■ Nvidia mental ray
- ◤ Nvidia Optix
- ◣ Nvidia IRay/Optix
- ☆ STELLAR
- ▲ REDsdk

- ● standard feature
- ◉ tweaking possible
- ○ data not provided / not supported

visualisation (images)

Category	Feature	mental ray/Standalone	Iray	Lightworks Iray+	DAZ Studio Pro	FurryBall RT	RealityServer	m4d	[0x1] IrayForMaya	Bloom Unit	FUZOR	DS Bunkspeed	Vray	Corona renderer	OctaneRenderer	Maxwell Render	FELIX Render	LuxRender	Thea renderer	Cinema 4D render	Renderworks	CineRender	Artlantis	Render[in]	AIR	Arion	moskitoRender	FinalRender	indigo RT	indigo renderer	Brazil	MODO render	Twilight Render
light sources	natural - sun and sky (CIE/Perez)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○	●	●
	natural - sun and sky (Preenham)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	natural - sun and sky (Hosek-Wilkie)												●	●			●										●			●			
	image-based (HDRI) lighting	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	artificial - IES/EULUMDAT (luminaires)	●	●	●	●	●	○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
geometry	solid (NURBS)										●						○								●								
	polygon mesh	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
simulations/ analyses	rendering/visualisation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	photometric (illum.-lum.)									○	●									●													
	radiometric (irrad.-rad.)		●	●																													
	daylighting (point-in-time)									◉							◉																
	BAPV/roof-mounted PV energy yield		◉	◉																													
	BIPV energy yield		◉	◉																													
	lighting									●									●														
	floating point images output	●	●	●	●	●	○		●	●	●	●	●	●	●	●	●	●	●	●	●	○	●	●	●	●	○	●	●	●		●	●
accuracy of calculation	unbiased (physically-based)	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	●				●	●	●	●	●	●	○		●	
	biased calculation	●	●			●		●			●	●	●	●		●					●	●			●						○	●	
radiosity	radiosity										●										●	●											
raytracing	forward (from light source)																																
	backward (from camera, sensor)	●	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●				●		●	●				●	●	
	bi-directional												●		●	●	●							●			●	●				●	
hybrid calculation	radiosity+raytracing										●																						
	rasterization+raytracing					●																											
light spectrum	visible - RGB)	●	●	●	●	●	●	●	●	●	●	●	●							●	●	●		●			●				●	●	
	visible - spectral													●	●	●	●									●	●		●	●			
BSDF	Material Definition Language	●	●	●	●	●	●	●	●	●	●	●																					
	custom material BRDF	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○	○	○	○	○	○	○	●	●	●	●	●	●	●	●	○
	basic materials BRDF	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
scale	urban	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	building	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	single room	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	module (facade component)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
design phase	conceptual/early phase		●	●		●					●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	○
	schematic	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	design development	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
design workflow	real-time simulation/progressive		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●		●	●	●	●	●	●	●	○
	parametric design (node based)	●	●	●		●			●		●		●	●	●	●		○		●	●	●				●	●					●	
computation	CPU based	●	●	●	●			●	●		●	●	●	●		●		●	●	●	●	●	●	●	●		●	●	●	●	●	●	●
	GPU based	●	●	●	●	●		●	●		●	●	●		●		●	●	●		●	●		●		●			●	●		●	
	multi-threading	●	●	●	●			●	●		●	●	●	●		●		●	●	●	●	●	●	●	●		●	●	●	●	○	●	○
	local network (multi-node)	●	●	●	○	●			●		○	○	●	●		●		○	○	●	●	●		○	○	●	○	●	●	●	○	●	
	web/cloud	●	●				●			●																							
system	graphical user-interface	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	open-source																	●															
	Windows	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Mac OSX	●	●		●	◉	●	●	●			○	●		●	●		●	●	●	●	●	●	●			●				●	●	●
	UNIX (Linux)		●			◉	●					○	●		●			●		●					●					●		●	
integration general	stand alone	●			●	●	●					●	●	●			●	●	●					●		●	●	●				●	
	3D plugin	●	●	●				●	●	●			●	●	●			●	●	●	●	●			●	●	●	●	●	●	●	●	●
	CAAD/CAM/BIM integrated plugin		●								●		●							●	●	●			●	●						●	
	(online/cloud/app) web based		●				●																										
interoperability	DDE (dynamic data exchange)	◉								●	●	◉	◉	◉	●			●															
	CAD interop. (fbx, dwg, sat, obj, IGES)		●	●	●	●	●	●	●		●	●	●		●	●				●	●	●	●	●	●	●	●	●		●	●	●	●
	BIM interoperability (gbXML, IFC)										●	●					●				●	●	●							●	●		
pricing	freeware				●													●															
	free for educational/non comercial	●				●					○			●	●			●			●												
	educational/student discount				●	●					○	●	●	●		●	○		●						●				●	●	●		
	payware	●		●		●		●				●	●	●	●		●		●					●	●	●	●	●	●	●	●		
	flexible payment options				●	●	●				●		●			●									●	●	●	●					●
	bundled	●	●																		●	●	●										
validation	validated (CIE 171:2006)	●		●																													

Legend:

- ▼ Cinema 4D render
- ▽ Maxwell Render
- ■ Nvidia mental ray
- ◤ Nvidia Optix
- ↘ Nvidia IRay/Optix
- ☆ STELLAR
- ▲ REDsdk

- ● standard feature
- ◉ tweaking possible
- ○ data not provided / not supported

category	feature	appleseed	NOX	lucile	RenderZone	Spectral Studio	FluidRay	Kray	Shaderlight	Mitsuba	pbrt	Raylectron	SU Podium	LightUp	LightWave	KERKYTHEA	POV-Ray	YafaRay	Redshift	Toolbag	Cycles	RaySupreme 3D	nXtRender/AccuRender nXt	Flamingo nXt	Caravaggio	Click-VR Visualizer	REDsdk ▲	ARTISAN	Renditioner Pro	VRED	KeyShot	DS 3DEXCITE DELTAGEN ☆	LAGOA
light sources	natural - sun and sky (CIE/Perez)	◉	◉		◉	◉	◉			◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉		◉	◉	◉	○	○	◉	◉	◉	◉	◉	◉
	natural - sun and sky (Preenham)	●	◉	●	◉	○	●		●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●		●	●	●	●	●	◉	●
	natural - sun and sky (Hosek-Wilkie)		●							●											●												
	image-based (HDRI) lighting	●	●		●	●	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	○		●	●	●	●	●	●
	artificial - IES/EULUMDAT (luminaires)	●	◉	○	●	●	●	○	●	○	○	●	●	●	●	●	●	●	●	●	●	○	●	●	○		○			●	●	●	○
geometry	solid (NURBS)																													●	●	●	●
	polygon mesh	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
simulations/ analyses	rendering/visualisation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	photometric (illum.-lum.)													●									●							●	○		
	radiometric (irrad.-rad.)									●				●																●	○		
	daylighting (point-in-time)									◉				●																			
	BAPV/roof-mounted PV energy yield																																
	BIPV energy yield																																
	lighting													●									●										
	floating point images output	●	●	●	○	●	●	●	○	○	●	○	●	○	●	○	●	●	●	●	●	●	○	○	○	●	○	○	○	●	●	●	○
accuracy of calculation	unbiased (physically-based)	●	●	●	●	●	●	●	○	●	●		●	●	●		●	●			●	●	●	●		○	○	○	●	●	●	●	
	biased calculation							○	●	●	●	●			●	●	●	●		●	●		●	●	○	○							
radiosity	radiosity														●								●										
raytracing	forward (from light source)																																
	backward (from camera, sensor)	●			●	●	●		●			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	bi-directional		●					●		●	●					●		●					●										
hybrid calculation	radiosity+raytracing															●							○										
	rasterization+raytracing																																
light spectrum	visible - RGB	●	●	●	●		●	●	●				●	●	●	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●
	visible - spectral	●					●	●			●	●																		●			
BSDF	Material Definition Language																												○				
	custom material BRDF	●	●	○	○	●	●	○	○		●	●	○	○	○	●	○	●	●	●	●	○	○	○		○	●	●	○	●	●	●	●
	basic materials BRDF	●	●	●	●	●	●	●	○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
scale	urban	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	building	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	single room	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	module (facade component)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
design phase	conceptual/early phase	●			●	●	●		●				●	●	●				●	●	●	●		●	●	●	●	●	●	●	●	●	●
	schematic	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	design development	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
design workflow	real-time simulation/progressive	●			●	●	●	○	●			●	●	●	○		●	○	●	●	●	●	●			●	●	●	●	●	●	●	●
	parametric design (node based)					●									●						●									●	●	●	●
computation	CPU based	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	○	●			●	●	●	●	●
	GPU based					●								●					●	●	●				○	●	○			●		●	
	multi-threading	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○		●	●	●	●	●	○	●	●	○		●	●	●	●
	local network (multi-node)		○	○	○	○	○	○	○			○				●	○	○	○			○	○		●	○	●			○	●		
	web/cloud									●																				●	●	●	●
system	graphical user-interface	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	open-source	●	●	●						●	●					●	●	●			●												
	Windows	●	●	●	●	○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Mac OSX	○	○	◉	●	○	●	●	●	●	●			●	●	●		●		●	●						●	●	●		●	●	●
	UNIX (Linux)	○	○	◉		○				●	●				●			●			●							●				●	●
integration general	stand alone	●	●	●		●	●			●	●				●	●		●		●		●			●			●		●	●	●	●
	3D plugin		●	●	●		●	●	●	●		●	●	●	●		●	●	●	●	●		●			●	●	●		●	●		
	CAAD/CAM/BIM integrated plugin				●				●														●	●	●					●	●		
	(online/cloud/app) web based																																
interoperability	DDE (dynamic data exchange)				●									◉										●			●			●	●	●	
	CAD interop. (fbx, dwg, sat, obj, IGES)	●	●	●	●	●	●	●	●	●	○	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●		●	●	●	●
	BIM interoperability (gbXML, IFC)				●				●				●	●	●			●					●		●					●			
pricing	freeware	●	●	●						●	●				●	●	●				●		●				●						
	free for educational/non comercial					○																					○		●				○
	educational/student discount					○		●	●				●										●				○			●	●	●	○
	payware					●	●	●	●			●	●	●					●	●		●		●		●	●	●	●	●	●	●	○
	flexible payment options					○																											○
	bundled				●													●				●		●									
validation	validated (CIE 171:2006)																															●	

Comparison table of rendering / visualisation software and game engines.

Legend:
- ▼ Unity
- ▽ RenderMan
- ↘ Nvidia IRay/Optix

Symbols:
- ● standard feature
- ◉ tweaking possible
- ○ data not provided
- (blank) not supported

		Showcase	CL3VER	REALIS3D ▼	Houdini Mantra	clarisse iFX	Guerilla Render	RenderMan ▽	3delight	Arnold	Lumion	Lumenrt	Twinmotion	Unity 3D	Unreal Engine	CRYENGINE	Brigade	Mizuchi	Delta	Torque 3D	Stingray	Frostbite
		visualisation (animations, real-time presentation)												game engines								
light sources	natural - sun and sky (CIE/Perez)	◉	◉	◉	◉	◉	◉	◉	◉	◉		◉	◉	◉	◉	◉	○	○	○	○		◉
	natural - sun and sky (Preenham)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○	○	○	○		●
	natural - sun and sky (Hosek-Wilkie)									●												
	image-based (HDRI) lighting	●	●	●	●	●	●	●	●	○	●	●	●	●	●	●	●	●	●	●	●	●
	artificial - IES/EULUMDAT (luminaires)	●	○	●	●	●	●	●	●	○	●	●	●	●	○	○	●	○	○	○		●
geometry	solid (NURBS)	○																				
	polygon mesh	○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
simulations/ analyses	rendering/visualisation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	photometric (illum.-lum.)																					●
	radiometric (irrad.-rad.)																					
	daylighting (point-in-time)																					
	BAPV/roof-mounted PV energy yield																					
	BIPV energy yield																					
	lighting																					●
	floating point images output	●	○	○	●	●	●	●	●	●	○	●	○	○	○	○	○	○	○	○	○	●
accuracy	unbiased (physically-based) calculation	●	●		●	○	●	●	●	●	○	○				●	●	●	○			●
	biased calculation	●		●	●	○		●	●	●	○	○	●	●	●	●				○	●	●
radiosity	radiosity										○	○										
raytracing	forward (from light source)																					
	backward (from camera, sensor)	●	●	●			●	●		●	○	○	●	●	●	●		○	●	●	●	●
	bi-directional (MLT, photon mapping)				●		●	●									●					●
hybrid calculation	radiosity+raytracing										○	○										
	rasterization+raytracing			●							○	○	●	●		●			●	●	●	●
light spectrum	visible - RGB	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	visible - spectral																					
BSDF	Material Definition Language (MDL)		○																			
	custom material BRDF		●	○	●	●	●	●	●	●	○	○		○	○	●	●	●	○	●	●	●
	basic materials BRDF	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
scale	urban	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	building	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	single room	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	module (facade component)																					
design phase	conceptual/early phase	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	schematic	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	design development	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
design workflow	real-time simulation/progressive	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	parametric design (node based)			●	●	●		●	●	●				●	●	●	○	○	○	○	●	●
computation	CPU based	●		●	●	●	●	●	●	●	●	●	○					●			○	○
	GPU based	●		●			●		●					●	●	●	●	●	●	●	○	○
	multi-threading	●		○	●	●	●	●	●	●	●	●	○	●	●			○			○	○
	local network (multi-node)	○			○	●	○	●	●		●	○										
	web/cloud	●	●	●				●						●								
system	graphical user-interface	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	open-source			●		●								○	○	○	○	○	○	●	○	○
	Windows	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Mac OSX			●	●	●	●	●	○	●	○	●		●			○	○	○	●		○
	UNIX (Linux)			●	○	●	●	●	●	○	○	○		●						●		○
pricing	freeware			●			●		●			●		●	●		○	○		●	●	○
	free for educational/non comercial use	●				●		●				●					○	○				○
	educational/student discount									●	●											○
	payware			●		●			●	●	●		●				●	○				○
	flexible payment options (subscription)	●	●											●	○	○			●		●	○
	bundled	●			●																	
validation	validated (CIE 171:2006)	○																				

Software comparison matrix — integration, interoperability, pricing, validation

Legend (engines):
▼ Radiance · ▽ DAYSIM · ■ A360 · ⊾ Nvidia Optix · ⊿ Nvidia IRay/Optix · ☆ PHANIE · ▲ EnergyPlus · △ OpenStudio · □ DOE

Legend (cells):
● standard feature · ⊘ tweaking possible · ○ data not provided / not supported

Column groups: **optical design/multiphysics** (TracePro … COMSOL) · **daylighting/whole building energy** (TAS Engineering … AECOsim Building Designer, ArchiWIZARD) · **urban** (ARCHSIM, umi – urban daylighting)

Category	Item	TracePro	Photopia	OpticStudio	ASAP	FRED	OpticCAD	LightTools	SPEOS, THEIA RT	Integra Lumicept	LucidShape	OSLO	OpTalX	COMSOL	TAS Engineering	OpenStudio	Sefaira	DesignBuilder	IES-VE	Green Building Studio	BSim	Honeybee	Mr. Comfy	COMFEN	ODS Studio	Vabi building perf.	AECOsim Bldg Designer	ArchiWIZARD	ARCHSIM	umi
integration CAAD	AutoCAD													●																
	Freecad																													
integration BIM	Revit													●		●		●	●								●	●		
	ARCHICAD																											●		
	Vectorworks Architect																	●										●		
	ALLPLAN ARCHITECTURE																											●		
	Microstation (Parasolid)																													
	AECOsim Building Designer																				●									
	Digital Project																													
	Trelligence Affinity																			●										
	Edificius																													
	Caddie																													
	DDS-CAD																													
	BrisCAD																													
	ZWCAD Architecture																													
	TurboCAD																													
	Architect3D																													
	Envisioneer																											●		
	ArchiTECH.PC																											●		
integration CAD/CAM	Rhinoceros 3D										●											●	●						●	●
	Alias																													
	Inventor			●									●																	
	CATIA								●		●		●																	
	Solidworks	●	●	●	●			●	●				●																	
	Inspire																													
	Evolve																													
	Creo			●				●					●																	
	Creo Parametric/Pro/ENGINEER												●																	
	Siemens NX (Parasolid)								●																					
	Solid Edge (Parasolid)												●																	
	TopSolid (Parasolid)																													
	SpaceClaim																													
	IronCAD																													
	Geomagic Design																													
	KOMPAS-3D																													
integration general 3D	SketchUp														●	●		●											●	
	FormIt 360/Pro																			●										
	3Ds max																													
	Maya																													
	Lightwave																													
	Cinema 4D																													
	Blender																								●					
	Poser																													
	Carrara																													
	DAZ Studio																													
	Houdini																													
	MODO																													
	formZ																													
	Bonzai3D																													
integration general	stand alone	●	●	●	●	●	●	●		●	●	●	●	●	●	●		●	●					●				●		
	3D plugin															●	●								●					
	CAAD/BIM integrated plugin	●	●	●	●			●	●	○				●		●	●	●	●			●	●	●			●	●	●	●
	(online/cloud/app) web based																●		●							●				
interoperability	live link – dynamic data exchange	⊘	⊘	⊘	⊘	○		⊘		○	⊘			●	⊘			●	●		⊘	⊘			⊘		⊘	●		
	CAD interop. (fbx, dwg, sat, obj, IGES)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●					●			●	●	
	BIM interoperability (gbXML, IFC)												○	○	●	●	●	●	●	●					●			●	⊘	⊘
pricing	freeware														●	●						●	●	●	●					●
	free for educational/non-comercial		○			○	○		○	○	○	○	○				●	●	●										○	○
	educational/student discount	●	○		○			○	○	○	○	○	●			●	●	●	●										○	○
	payware	●	●	●	●	●	●	●	●	●	●	●	○	●			●	●	●							●	●	●		
	flexible payment (subscription)																								●		●			
	bundled																●	●	●									●		
validation	validated (CIE 171:2006)	●	○	○	○	○	○	○	●	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●		●	○	●	●

Legend

Symbol	Meaning
▼	Radiance
▽	DAYSIM
■	A360
◸	Nvidia Optix
◺	Nvidia IRay/Optix
☆	PHANIE
▲	EnergyPlus
△	OpenStudio
□	DOE
●	standard feature
◐	tweaking possible
○	data not provided / not supported

daylighting/lighting/solar

Column tools (left→right): Radiance - classic · Radiance - DAYSIM · Radiance - photon map · Diva ▽ · DAYSIMpm ▽ · IDA ICE ▽ · SPOT ▽ · ReluxSuite / Pro ▼ · Accelerad ▽ · Geronimo ▽ · DIAL+Suite ☆ · su2ds ▽ · LightStanza ▼ · Light Studio ▽ · Rayfront ▼ · Lighting Analysis for Revit ■ · Solar Analysis tool ■ · VELUX Daylight Visualizer ◹ · AGi32 · ElumTools ▼ · Lightsolve ▼ · LightUpAnalytics · DIALux (4, evo) · LightCalc · CSTB D1 PHANIE-2010 · ecoBIM (TAS Engineering) · LD Assistant · Shadow Analysis · Chronolux · Ocean · BIM IQ ▷

category	feature	Rad-classic	Rad-DAYSIM	Rad-photon map	Diva	DAYSIMpm	IDA ICE	SPOT	ReluxSuite/Pro	Accelerad	Geronimo	DIAL+Suite	su2ds	LightStanza	Light Studio	Rayfront	Lighting Analysis for Revit	Solar Analysis tool	VELUX Daylight Vis.	AGi32	ElumTools	Lightsolve	LightUpAnalytics	DIALux (4, evo)	LightCalc	CSTB D1 PHANIE-2010	ecoBIM (TAS Eng.)	LD Assistant	Shadow Analysis	Chronolux	Ocean	BIM IQ
integration CAAD	AutoCAD								●		●																					
	Freecad																															
integration BIM	Revit																●	●			●											
	ARCHICAD																															
	Vectorworks Architect																															
	ALLPLAN ARCHITECTURE																															
	Microstation (Parasolid)																															
	AECOsim Building Designer																															
	Digital Project																															
	Trelligence Affinity																															
	Edificius																															
	Caddie																															
	DDS-CAD																															
	BrisCAD																															
	ZWCAD Architecture																															
	TurboCAD																															
	Architect3D																															
	Envisioneer																															
	ArchiTECH.PC																															
integration CAD/CAM	Rhinoceros 3D				●																											
	Alias																															
	Inventor																															
	CATIA																															
	Solidworks																															
	Inspire																															
	Evolve																															
	Creo																															
	Creo Parametric/Pro/ENGINEER																															
	Siemens NX (Parasolid)																															
	Solid Edge (Parasolid)																															
	TopSolid (Parasolid)																															
	SpaceClaim																															
	IronCAD																															
	Geomagic Design																															
	KOMPAS-3D																															
integration general 3D	SketchUp												●	●								●	●						●	●		
	FormIt 360/Pro																		●													
	3Ds max															●																
	Maya																															
	Lightwave																															
	Cinema 4D																															
	Blender																															
	Poser																															
	Carrara																															
	DAZ Studio																															
	Houdini																															
	MODO																															
	formZ																															
	Bonzai3D																															
integration general	stand alone	●	●	●		●	●	●	●	●	●	●				●			●	●				●	●	●	●			●	●	○
	3D plugin												●		●			●					●						●	●	●	○
	CAAD/BIM integrated plugin				●				●		●							●	●			●									●	○
	(online/cloud/app) web based													●																		○
interoperability	live link - dynamic data exchange				◐				●								○	●														
	CAD interop. (fbx, dwg, sat, obj, IGES)				●			●	●				●	●	●	●	●	●	●	●	●	●	●	●	●	○	●	●			●	●
	BIM interoperability (gbXML, IFC)							●									●	●				●	●	●			●		●	●		
pricing	freeware	●	●	●		●				●	●		●			○					●				●		●					
	free for educational/non-comercial						○					●				○					●	●										○
	educational/student discount				●		○						○	●	○																	○
	payware				●		●	●			●			●	●			●			●	●		●				●			●	●
	flexible payment (subscription)													●				●	●											●	●	○
	bundled																●	●														
validation	validated (CIE 171:2006)	●	●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●					●					

visualisation (images)

integration	software	mental ray/Standalone	Iray	Lightworks Iray+	DAZ Studio Pro	FurryBall RT	RealityServer	m4d	[0x1] IrayForMaya	Bloom Unit	FUZOR	DS Bunkspeed	Vray	Corona renderer	OctaneRenderer	Maxwell Render	FELIX Render	LuxRender	Thea renderer	Cinema 4D render	Renderworks	CineRender	Artlantis	Render[in]	AIR	Arion	moskitoRender	FinalRender	indigo RT	indigo renderer	Brazil	MODO render	Twilight Render
CAAD	AutoCAD														●																		
CAAD	Freecad																																
BIM	Revit										●			●	●																●		
BIM	ARCHICAD													●	●							●											
BIM	Vectorworks Architect																				●												
BIM	ALLPLAN ARCHITECTURE																					●											
BIM	Microstation (Parasolid)															●																●	
BIM	AECOsim Building Designer																																
BIM	Digital Project	●																															
BIM	Trelligence Affinity																																
BIM	Edificius																																
BIM	Caddie		●																														
BIM	DDS-CAD																																
BIM	BrisCAD																																
BIM	ZWCAD Architecture																																
BIM	TurboCAD																																
BIM	Architect3D			●																													
BIM	Envisioneer																																
BIM	ArchiTECH.PC																																
CAD/CAM	Rhinoceros 3D		●										●	●	●				●						●	●				●			
CAD/CAM	Alias																																
CAD/CAM	Inventor												●																				
CAD/CAM	CATIA		●																														
CAD/CAM	Solidworks		●													●																	
CAD/CAM	Inspire															●																	
CAD/CAM	Evolve															●																	
CAD/CAM	Creo																																
CAD/CAM	Creo Parametric/Pro/ENGINEER																																
CAD/CAM	Siemens NX (Parasolid)																																
CAD/CAM	Solid Edge (Parasolid)																																
CAD/CAM	TopSolid (Parasolid)																																
CAD/CAM	SpaceClaim																																
CAD/CAM	IronCAD																																
CAD/CAM	Geomagic Design																																
CAD/CAM	KOMPAS-3D																																
general 3D	SketchUp						●			●			●	●	●				●						●								●
general 3D	FormIt 360/Pro																																
general 3D	3Ds max	●	●	●		●							●	●	●	●			●							●	●	●					
general 3D	Maya	●	●			●			●				●	●	●	●										●							
general 3D	Lightwave														●	●																	
general 3D	Cinema 4D	●	●			●		●					●	●	●	●	●	●	●	●					●	●		●		●			
general 3D	Blender												●	●	●					●													
general 3D	Poser													●																			
general 3D	Carrara													●																			
general 3D	DAZ Studio													●																			
general 3D	Houdini	●												●	●																		
general 3D	MODO													●	●																	●	
general 3D	formZ													●																			
general 3D	Bonzai3D													●																			

visualisation (images)

Legend:
- ▼ Cinema 4D render
- ▽ Maxwell Render
- ■ Nvidia mental ray
- ◤ Nvidia Optix
- ◿ Nvidia IRay/Optix
- ☆ STELLAR
- ▲ REDsdk

- ✓ standard feature
- ⊘ tweaking possible
- ○ data not provided / not supported

integration	software	appleseed	NOX	lucile	RenderZone	Spectral Studio	FluidRay	Kray	Shaderlight	Mitsuba	pbrt	Raylectron	SU Podium	LightUp	LightWave	KERKYTHEA	POV-Ray	YafaRay	Redshift	Toolbag	Cycles	RaySupreme 3D	nXtRender/AccuRender nXt	Flamingo nXt	Caravaggio	Click-VR Visualizer	REDsdk ▲	ARTISAN	Renditioner Pro	VRED	KeyShot	DS 3DEXCITE DELTAGEN ☆	LAGOA
CAAD	AutoCAD																						✓										
CAAD	Freecad																																
BIM	Revit																						✓										
BIM	ARCHICAD																																
BIM	Vectorworks Architect																																
BIM	ALLPLAN ARCHITECTURE																																
BIM	Microstation (Parasolid)																																
BIM	AECOsim Building Designer																																
BIM	Digital Project																																
BIM	Trelligence Affinity																																
BIM	Edificius																																
BIM	Caddie																																
BIM	DDS-CAD																																
BIM	BrisCAD																											✓					
BIM	ZWCAD Architecture																											✓					
BIM	TurboCAD																										✓						
BIM	Architect3D																																
BIM	Envisioneer																																
BIM	ArchiTECH.PC																																
CAD/CAM	Rhinoceros 3D						✓			✓												✓	✓	✓							✓		
CAD/CAM	Alias																													✓			
CAD/CAM	Inventor																																
CAD/CAM	CATIA																																
CAD/CAM	Solidworks																														✓		
CAD/CAM	Inspire																																
CAD/CAM	Evolve																														✓		
CAD/CAM	Creo																													✓	✓		
CAD/CAM	Creo Parametric/Pro/ENGINEER																																
CAD/CAM	Siemens NX (Parasolid)																										✓				✓		
CAD/CAM	Solid Edge (Parasolid)																										✓				✓		
CAD/CAM	TopSolid (Parasolid)																										✓						
CAD/CAM	SpaceClaim																														✓		
CAD/CAM	IronCAD																														✓		
CAD/CAM	Geomagic Design																														✓		
CAD/CAM	KOMPAS-3D																												✓				
general 3D	SketchUp						✓		✓	✓		✓	✓	✓			✓					✓			✓				✓	✓	✓		
general 3D	FormIt 360/Pro																																
general 3D	3Ds max		✓	✓											✓											✓	✓				✓		
general 3D	Maya														✓																		
general 3D	Lightwave							✓							✓																		
general 3D	Cinema 4D																																
general 3D	Blender	✓																✓			✓												
general 3D	Poser									✓																							
general 3D	Carrara																																
general 3D	DAZ Studio																																
general 3D	Houdini																																
general 3D	MODO																																
general 3D	formZ				✓																												
general 3D	Bonzai3D																																

Legend:

- ▼ Unity
- ▽ RenderMan
- ↘ Nvidia IRay/Optix

- ✓ standard feature
- ⊘ tweaking possible
- ○ data not provided / not supported

		visualisation (animations, real-time presentation)												game engines								
		Showcase	CL3VER▷	REALIS3D▼	Houdini Mantra	clarisse iFX	Guerilla Render	RenderMan	3delight ▽	Arnold	Lumion	Lument	Twinmotion	Unity 3D	Unreal Engine	CRYENGINE	Brigade	Mizuchi	Delta	Torque 3D	Stingray	Frostbite
integration CAAD	AutoCAD	✓																				
	Freecad																					
integration BIM	Revit										✓	✓									✓	
	ARCHICAD										✓	✓										
	Vectorworks Architect										✓											
	ALLPLAN ARCHITECTURE										✓											
	Microstation (Parasolid)										✓	✓										
	AECOsim Building Designer																					
	Digital Project																					
	Trelligence Affinity																					
	Edificius																					
	Caddie																					
	DDS-CAD																					
	BrisCAD																					
	ZWCAD Architecture																					
	TurboCAD																					
	Architect3D																					
	Envisioneer																					
	ArchiTECH.PC																					
integration CAD/CAM	Rhinoceros 3D									✓												
	Alias																					
	Inventor	✓																				
	CATIA																					
	Solidworks																					
	Inspire																					
	Evolve																					
	Creo																					
	Creo Parametric/Pro/ENGINEER																					
	Siemens NX (Parasolid)																					
	Solid Edge (Parasolid)																					
	TopSolid (Parasolid)																					
	SpaceClaim																					
	IronCAD																					
	Geomagic Design																					
	KOMPAS-3D																					
integration general 3D	SketchUp										✓	✓										
	FormIt 360/Pro																					
	3Ds max						✓				✓										✓	
	Maya					✓	✓	✓														
	Lightwave																					
	Cinema 4D					✓	✓	✓														
	Blender																					
	Poser																					
	Carrara																					
	DAZ Studio																					
	Houdini				✓					✓												
	MODO																					
	formZ																					
	Bonzai3D																					
integration general	stand alone	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	3D plugin								✓	✓											✓	○
	CAAD/CAM/BIM integrated plugin												✓								✓	○
	(online/cloud/app) web based		✓												✓							
interoperability	DDE (dynamic data exchange)	✓			⊘	⊘		✓	✓	✓			○								✓	○
	CAD interop. (fbx, dwg, sat, obj, IGES)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	BIM interoperability (gbXML, IFC)		✓																			

6. Conclusion

This review showed the most comprehensive review of the multidisciplinary solar design tools so far. Almost 200 tools were compared to about 70 features and their integration in around 50 3D, CAD/CAM and BIM software packages. For such an extensive review of around 21000 fields, tables were used to organize and present data in a straightforward way. Description part that preceded tables aimed to explain features that solar design tools use in order to analyze their capability for specific purposes. Since solar design tools has shown tendencies in spreading across multidisciplinary areas over the past years, this type of review was necessary in order to map innovative possibilities that can emerge. This paradigm shift should provide a framework for many areas to find common solutions to multi-performance concepts such as high-performance facades that can include many concepts such as kinetics, BIPV, CFS, DRS, phase-change materials in the same solution. Moreover, the review should broaden perspective of academics and practitioners from all included fields, all knowledge and experience levels to facilitate integration of their design processes. These two directions combined are expected to enable acceleration of innovative building and particularly façade solutions.

Appendix A. Appendix

A complete list of solar design tools, analyzed in this review, with information of their developers/software vendors and websites are presented in the following tables.

PV

Developer/Company	Product	Website
NREL - US National Renewable Energy Laboratory	System Advisor Model	https://sam.nrel.gov
PVsyst SA	PVsyst	http://www.pvsyst.com/en/
Valentin Software	PV*SOL	http://www.valentin-software.com/en/products/photovolta
Skelion	Skelion	http://www.skelion.com/index.htm
ACCA software S.p.A.	Solarius-PV	http://www.acca.it/software-impianti-fotovoltaici-gratis
Vela Solaris	Polysun	http://www.velasolaris.com/english/home.html
Solar Energy Laboratory at the University of Wisconsin	CECPV Calculator	http://www.gosolarcalifornia.org/tools/nshpcalculator/dov
NREL - US National Renewable Energy Laboratory	PVwatts	http://pvwatts.nrel.gov
NEMETSCHEK AG.	DDS-CAD PV	http://www.dds-cad.net/products/dds-cad-pv/
INSEL	INSEL	http://www.insel.eu/index.php?id=301&L=1
Solmetric	PV Designer	http://www.solmetric.com
F-Chart Software	PV F-CHART	http://www.fchart.com/fchart/
SMA Solar Technology AG	SMA Off-Grid Configurator	http://www.sma.de/en/products/planning-software/sma-o
Laplace System Co., Ltd.	SolarPro	http://www.lapsys.co.jp/english/products/pro.html
Trace Software International	Archelios Suite	http://www.archelios.com
Maui Solar Energy Software Corporation	PV-DesignPro	http://www.mauisolarsoftware.com
Natural Resources Canada	RETScreen Plus	http://www.retscreen.net/ang/home.php
HOMER Energy LLC	HOMER Pro	http://www.homerenergy.com/index.html
Solarschmiede	PVscout	http://www.solarschmiede.de/en/pvscout-20-premium
STÖHR+SAUER CAD- und Computersystem GmbH	HELIOS3D	http://www.helios3d.com/index.php/en/downloads

OPTICAL DESIGN

Developer/Company	Product	Website
Lambda Research Corporation	TracePro	http://www.lambdares.com
LTI Optics, LLC	Photopia	http://www.ltioptics.com/en/photopia-standalone-base.h
Zemax, LLC	OpticStudio	http://www.zemax.com/products/opticstudio/about
Breault Research Organization, Inc.	ASAP	http://www.breault.com/software/about-asap
Photon Engineering	FRED	http://photonengr.com/software/
OptiCAD Corp.	OptiCAD	http://www.opticad.com
Synopsys' Optical Solutions Group	LightTools	http://optics.synopsys.com/lighttools/
OPTIS	SPEOS, THEIA RT	http://www.optis-world.com/Product-offering/SPEOS
Integra Inc.	Lumicept	http://www.integra.jp/en/products/lumicept
Brandenburg GmbH	LucidShape	http://www.brandenburg-gmbh.de/products/lucidshape/
Sinclair Optics, Inc.	OSLO	http://www.sinopt.com
Optenso	OpTaliX	http://www.optenso.com
COMSOL Inc.	COMSOL	https://www.comsol.com/

DAYLIGHTING/WHOLE BUILDING ENERGY/URBAN

Developer/Company	Product	Website
EDSL	TAS Engineering	http://www.edsl.net/main/Software/Designer.aspx
NREL, ANL, LBNL, ORNL, and PNNL	OpenStudio	https://www.openstudio.net/
Sefaira	SEFAIRA ARCHITECTURE	http://sefaira.com/sefaira-architecture/
DesignBuilder Software Ltd	DesignBuilder	http://www.designbuilder.co.uk/content/view/160/226/
IES - Integrated Environmental Solutions Limited	IES-VE	https://www.iesve.com
Autodesk	Green Building Studio	https://gbs.autodesk.com/GBS/
Sbi - the Danish Building Research Institute	BSim - SimLight, Xsun	http://sbi.dk/en/bsim/about-bsim
Mostapha Sadeghipour Roudsari	Honeybee	http://www.food4rhino.com/project/ladybug-honeybee?e
Max C Doelling	Mr. Comfy	http://mrcomfy.org
LBNL - Lawrence Berkeley National Laboratory	COMFEN	https://windows.lbl.gov/software/comfen/comfen.html
ODS Engineering	ODS Studio	http://www.ods-engineering.com/tools/ods-studio/
Vabi Software B.V.	Vabi building performance	http://www.vabisoftware.com
Bentley Systems	AECOsim Building Designer	http://www.bentley.com/en-US/Products/AECOsim+Build
GRAITEC	ArchiWIZARD	http://www.graitec.com/fr/archiwizard.asp
Timur Dogan	ARCHSIM	http://archsim.com
Sustainable Design Lab at the MIT	umi - urban daylighting	http://urbanmodellinginterface.ning.com

DAYLIGHTING/LIGHTING/SOLAR

Developer/Company	Product	Website
LBNL - Lawrence Berkeley National Laboratory	RADIANCE – classic	http://www.radiance-online.org
Christoph Reinhart, Fraunhofer ISE, Harvard Uni., MIT, NRC	RADIANCE – DAYSIM	http://daysim.ning.com
LBNL - Lawrence Berkeley National Laboratory	RADIANCE – genBSDF	http://radsite.lbl.gov/radiance/man_html/genBSDF.1.html
Roland Schregle - Fraunhofer ISE, HSLU	RADIANCE - photon map	http://www.ise.fraunhofer.de/en/
Harvard University, Solemma LLC	Diva	http://diva4rhino.com
Penn State University	DAYSIMpm	http://daysim.ning.com/page/download
EQUA Simulation AB	IDA ICE	http://www.equa.se/en/ida-ice
Daylighting Innovations	SPOT	https://www.daylightinginnovations.com/spot-home
Relux Informatik AG	ReluxSuite	http://www.relux.biz
Nathaniel Jones and Christoph Reinhart, MIT	Accelerad	http://web.mit.edu/sustainabledesignlab/projects/Acceler
J. Kaempf, C. Basurto, J.-L. Scartezzini - EPFL LESO	Geronimo	http://leso.epfl.ch/geronimo
Estia SA	DIAL+Suite	http://www.dialplus.ch/#!home/c16nd
Josh Kjenner, Thomas Bleicher	su2ds	https://code.google.com/p/su2ds/
Die Lichtplaner	Light Studio	http://www.lightstudio.at/default_e.asp
Light Foundry, LLC	LightStanza	http://lightstanza.com
Autodesk	Lighting Analysis for Revit	http://www.autodesk.com/products/lighting-analysis-revit
Autodesk	Solar Analysis tool	https://beta.autodesk.com/callout/?callid=A85F5FB1124
VELUX, LUXION	VELUX Daylight Visualizer	http://viz.velux.com/daylight_visualizer/about
Lighting Analysts	AGi32	http://www.agi32.com/index.php?id=11
Lighting Analysts	ElumTools	http://www.elumtools.com/index.php?id=1
EPFL LIPID	Lightsolve	http://lightsolve.epfl.ch
LightUp Analytics Ltd.	LightUpAnalytics	http://www.lightup-analytics.com
DIAL GmbH	DIALux	http://www.dial.de/DIAL/en/dialux/about.html
Enviro-Systems	LightCalc	http://www.lightcalc.com
CSTB	PHANIE	http://www.cstb.fr/dae/en/nos-produits-et-formations/out
Cadline	ecoBIM	http://www.cadline.co.uk/Products/BIM/Products/ecoBIM
Design & Drafting	LD Assistant	http://www.ldassistant.com
ArchiWIZARD	ArchiWIZARD V3 Plug-in	https://extensions.sketchup.com/en/content/plug-archiwi
DeltaCodes Sp. z o.o	Shadow Analysis	http://www.deltacodes.pl/en
Links' System Software	Chronolux	https://sites.google.com/site/lssoft2011/home/chronolux
Eclat-Digital Recherche	Ocean	http://www.eclat-digital.com
Oldcastle BuildingEnvelope, NVIDIA	BIM IQ	http://www.bimiq.com

VISUALISATION (animations)

Developer/Company	Product	Website
Autodesk	Autodesk Showcase	http://www.autodesk.com/products/showcase/overview
CL3VER, NVIDIA	CL3VER	https://www.cl3ver.com
REAL VISUAL GROUP LTD	REALIS3D	http://realis3d.com/#intro
Side Effects Software Inc.	Houdini Mantra	http://www.sidefx.com/index.php?option=com_content&
Isotropix SAS.	clarisse iFX	http://www.isotropix.com/index.php?to=products&produ
Mercenaries Engineering	Guerilla Render	http://guerillarender.com
Pixar	RenderMan	https://renderman.pixar.com/view/renderman
DNA Research	3delight	http://www.3delight.com/en/index.php
Solid Angle S.L.	Arnold	https://www.solidangle.com
Act-3D B.V.	Lumion/PRO	http://lumion3d.com
e-on software, inc.	Lumenrt	http://www.lumenrt.com
Abvent Group	Twinmotion	http://vador.abvent.com/twinmotion/?lang=en

GAME ENGINES

Developer/Company	Product	Website
Unity Technologies	Unity 3D	https://unity3d.com
EPIC GAMES, INC.	Unreal Engine	https://www.unrealengine.com/previous-versions
Crytek	CRYENGINE	http://www.crytek.com/cryengine
OTOY	Brigade	https://brigade.otoy.com
Silicon Studio Corp.	Mizuchi	http://www.siliconstudio.co.jp/middleware/mizuchi/en/
Delta Engine GmbH	Delta Engine	http://deltaengine.net
GarageGames	Torque 3D	http://www.garagegames.com/products/torque-3d
Autodesk	Stingray	http://www.autodesk.com/products/stingray/overview
Frostbite	Frostbite	http://www.frostbite.com

VISUALISATION (images)

Developer/Company	Product	Website
Autodesk, NVIDIA	mental ray/Standalone	http://www.nvidia-arc.com/mentalray.html / http://www.a
Autodesk, NVIDIA	Iray	http://www.nvidia-arc.com/iray.html /
Lightworks, NVIDIA	Lightworks Iray+	http://www.lightworks-iray.com
DAZ Productions, Inc., NVIDIA	DAZ Studio Pro	http://www.daz3d.com/daz_studio
Art And Animation studio, NVIDIA	FurryBall RT	http://furryball.aaa-studio.eu
migenius, NVIDIA	RealityServer	http://www.migenius.com
at² GmbH	m4d	http://www.m4d.info/index.php
[0x1] Software und Consluting GmbH	[0x1] IrayForMaya	http://www.0x1-software.com/en/produkte/0x1-irayforma
migenius, NVIDIA	Bloom Unit	https://www.bloomunit.com/en/
Kalloc Studios	FUZOR	https://www.kalloctech.com
Chaos Group	Vray	http://www.chaosgroup.com/en/2/index.html
Render Legion s.r.o.	Corona renderer	https://corona-renderer.com
OTOY Inc	OctaneRenderer	https://home.otoy.com/render/octane-render/
Next Limit	Maxwell Render	http://www.maxwellrender.com/
Legal Stack! Studios	FELIX Render	http://www.felixrender.com
LuxRender	LuxRender	http://www.luxrender.net/en_GB/index
Solid Iris Technologies	Thea renderer	https://www.thearender.com/site/
MAXON Computer GmbH	Cinema 4D render	http://www.maxon.net/products/cinema-4d-visualize/rend
Nemetschek Vectorworks, Inc.	Vectorworks Renderworks	http://www.vectorworks.net/renderworks/
Graphisoft, MAXON Computer GmbH	CineRender	http://www.maxon.net/pt/news/singleview-default/article/
Abvent Group	Artlantis	http://artlantis.com/en/home
Abvent Group	Render[in]	http://renderin.com
SiTex Graphics	AIR	http://www.sitexgraphics.com/html/air.html
RandomControl	Arion	http://www.randomcontrol.com/#1
cebas Visual Technology Inc.	moskitoRender	http://www.cebas.com/?pid=productinfo&prd_id=175
cebas Visual Technology Inc.	FinalRender	http://www.cebas.com/?pid=productinfo&prd_id=137
Glare Technologies Limited.	indigo RT	http://www.indigorenderer.com/indigo_rt
Glare Technologies Limited.	indigo renderer/for Revit	http://www.indigorenderer.com/indigo3
Robert McNeel & Associates	Brazil	http://brazil.rhino3d.com
THE FOUNDRY	MODO render	https://www.thefoundry.co.uk/products/modo/features/#F
Twilight Render LLC	Twilight Render	http://twilightrender.com
FRANÇOIS BEAUNE et al.	appleseed	http://appleseedhq.net
Evermotion	NOX	http://www.evermotion.org/nox
Fixstars Corporation	lucile	http://www.fixstars.com/en/lucille/
AutoDesSys, Inc.	RenderZone	http://www.formz.com/products/renderzone.html
Spectral Pixel	Spectral Studio	http://www.spectralpixel.com/products/ss_home.html
Fluid Interactive Inc.	FluidRay	http://www.fluidray.com
MindBerries	Kray	http://www.kraytracing.com
ArtVPS Ltd.	Shaderlight	https://www.artvps.com
Wenzel Jakob	Mitsuba	https://www.mitsuba-renderer.org
Matt Pharr, Greg Humphreys	pbrt	https://github.com/mmp/pbrt-v2
SoftByte Labs Inc.	Raylectron	http://raylectron.com/webver2/
Cadalog, Inc.	SU Podium	http://www.suplugins.com/
LightUp Ltd	LightUp	https://www.light-up.co.uk/
NewTek Inc.	LightWave	https://www.lightwave3d.com
Solid Iris Technologies	KERKYTHEA	http://www.kerkythea.net/cms/
Persistence of Vision Raytracer Pty. Ltd.	POV-Ray	http://www.povray.org
Alejandro Conty Estévez et al.	YafaRay	http://www.yafaray.org
Redshift Rendering Technologies, Inc.	Redshift	https://www.redshift3d.com
Marmoset LLC	Toolbag	https://www.marmoset.co/toolbag
Blender Foundation	Cycles	https://www.blender.org/features/
BrainDistrict GmbH.	RaySupreme 3D	http://www.braindistrict.com/en/raysupreme-3d
Render Plus Software	nXtRender/AccuRender nXt	http://www.renderplus.com/wp2/
Scott Davidson	Flamingo nXt	http://nxt.flamingo3d.com/page/product-overview
Caravaggio	Caravaggio RENDER	http://www.caravaggio3d.com/products/render
Codeblend	Click-VR Visualizer	http://www.codeblend.com/products/visualizer/
REDWAY3D S.A.S.	REDsdk	http://www.redway3d.com/products/redsdk/
Pictorex Ltd	ARTISAN	http://www.pictorex.com/index.php
IMSI/Design, LLC.	Renditioner Pro	http://www.imsidesign.com/Products/Renditioner
Autodesk	VRED	http://www.autodesk.com/products/vred/overview
LUXION	KeyShot	https://www.keyshot.com
Dassault Systèmes	DS Bunkspeed Shot, Pro	http://www.bunkspeed.com/#s=2
Dassault Systemes 3DExcite GmbH	DS 3DEXCITE DELTAGEN	https://www.rtt.ag/en
LAGOA	LAGOA	http://home.lagoa.com

CAAD

Developer/Company	Product	Website
Autodesk	AutoCAD	http://www.autodesk.com/products/autocad/overview
	Freecad	http://www.freecadweb.org

BIM

Developer/Company	Product	Website
Autodesk	Revit	http://www.autodesk.com/products/revit-family/overview
Graphisoft	ArchiCAD	http://www.graphisoft.com/archicad/
Nemetschek Vectorworks, Inc.	Vectorworks Architect	http://www.vectorworks.net/architect/
Allplan Deutschland GmbH	ALLPLAN ARCHITECTURE	http://www.allplan.com/en/software/architecture/allplan-a
Bentley Systems, Incorporated	Microstation (Parasolid)	http://www.bentley.com/en-US/Products/MicroStation/
Bentley Systems, Incorporated	AECOsim Building Designer	http://www.bentley.com/en-US/Products/AECOsim+Buil
Digital Project, Inc.	Digital Project	http://www.digitalproject3d.com
Trelligence, Inc.	Trelligence Affinity	http://www.trelligence.com/affinity_overview.php
ACCA software S.p.A.	Edificius	http://www.accasoftware.com/en/id4/bim.html
Caddie Software	Caddie	http://www.caddiesoftware.com/index.php
Data Design System	DDS-CAD	http://www.dds-cad.net
Bricsys	BrisCAD	https://www.bricsys.com/en_INTL/bricscad/
ZWCAD Software Co.	ZWCAD Architecture	http://www.zwsoft.com/zwcad/zwcad_architecture/
IMSI/Design, LLC.	TurboCAD	http://www.turbocad.com/TurboCAD/TurboCAD-Windov
Cadsoft Corporation	Envisioneer	http://www.cadsoft.com/products/
Onuma, Inc.	Onuma	http://www.onuma.com
Avanquest Software	Architect3D	http://www.myarchitect3d.com/
EDICAD	ArchiTECH.PC	http://www.edicad.com/Produit_APC.aspx

CAD/CAM

Developer/Company	Product	Website
Robert McNeel & Associates	Rhinoceros 3D	https://www.rhino3d.com
Autodesk	Alias	http://www.autodesk.com/products/alias-products/overv
Autodesk	Inventor	http://www.autodesk.com/products/inventor/overview
Dassault Systèmes	CATIA	http://www.3ds.com/products-services/catia
Dassault Systèmes	Solidworks	http://www.solidworks.com
solidThinking, Inc.	Inspire	http://www.solidthinking.com/ProductExperience.aspx?it
solidThinking, Inc.	Evolve	http://www.solidthinking.com/ProductOverview.aspx?iten
PTC Inc.	PTC Creo	http://www.ptc.com/product/creo
PTC Inc.	Creo Parametric/Pro/ENGINEER	http://www.ptc.com/cad/3d-cad/creo-parametric
Siemens Product Lifecycle Management Software Inc.	Siemens NX (Parasolid)	http://www.plm.automation.siemens.com/en_us/products
Siemens Product Lifecycle Management Software Inc.	Solid Edge (Parasolid)	http://www.plm.automation.siemens.com/en_us/products
Missler Software	TopSolid (Parasolid)	http://www.topsolid.com
SpaceClaim Corporation.	SpaceClaim	http://www.spaceclaim.com/en/default.aspx
IronCAD, LLC.	IronCAD	http://www.ironcad.com
Geomagic	Geomagic Design	http://www.geomagic.com/en/products/design/overview
ASCON	KOMPAS-3D	http://ascon.net/solutions/kompas_3d/

general 3D

Developer/Company	Product	Website
Trimble Navigation Limited	SketchUp	http://www.sketchup.com
Autodesk	FormIT 360	http://www.autodesk.com/products/formit-360/overview
Autodesk	3Ds max	http://www.autodesk.com/products/3ds-max/overview
Autodesk	Maya	http://www.autodesk.com/products/maya/overview
NewTek Inc.	Lightwave	https://www.lightwave3d.com
MAXON Computer	Cinema 4D	http://www.maxon.net/?id=1499
Blender.org	Blender	https://www.blender.org
Smith Micro Software, Inc.	Poser	http://my.smithmicro.com/poser-3d-animation-software.l
DAZ Productions, Inc.	Carrara	http://www.daz3d.com/carrara-8-5-pro
DAZ Productions, Inc.	DAZ Studio	http://www.daz3d.com/daz_studio
Side Effects Software Inc.	Houdini	http://www.sidefx.com
The Foundry Visionmongers Ltd	MODO	https://www.thefoundry.co.uk/products/modo/
AutoDesSys, Inc.	formZ	http://www.formz.com
AutoDesSys, Inc.	Bonzai3D	

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