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Daylighting Analysis and Simulation Tools in Architectural Design
-Review of Tools and Compatibility with Architectural CAD Platforms

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ABSTRACT

Purpose: This research is a review of current and past daylighting simulation tools from the perspective of the Architect, one of the key stakeholder in the integration of the science of daylighting into architectural practice. The review is evaluated based on criteria identified through existing literature. First, a review of integration and interoperability with mainstream architectural CAD platform is initiated and second an evaluation of select tools were performed based on a simple simulation task involving a typical classroom. **Method:** Over fifty daylighting simulation tools are categorized based on its integration and plotted on an "integration matrix" to illustrate compatibility with mainstream architectural software. The matrix is used as a basis to identify daylighting simulation tools for further evaluation. Evaluation of the tools are based on functionality, ease of use, and visualization. **Result:** Findings include recent increase in available daylighting simulation tools in the form of plug-ins to existing architectural CAD platforms. In addition, the integration matrix provides valuable information to architects and designers in the selection of Daylighting Simulation Tool, one of the key hurdles that designers face in the implementation of daylighting in architectural design practice. Furthermore, the evaluation of the tools provides information in the aid and development of future Daylighting Simulation Tools.

KEYWORD

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Daylighting Simulation
Daylighting Analysis
Computer-Aided Design
Graphic User Interface

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1. Introduction

1.1. Research Background and Purpose

Building simulation and analysis tools (including daylighting simulation tools) have been developed primarily by Engineers and Researchers for the purposes of analysis and research and often lacked visual means of expression. Even with developments in computer graphics, which addressed this issue, and the advent of new metrics and tools, the use by designers and architects remains limited, especially in early phases of architectural design (including concept and schematic design). During the early phases of design where the potential to impact the design is the greatest, Architects who have the most influence over design, preferred past experiences base on rule of thumb methods over computer simulation compared to later phases of design[11]. In fact, the gap between the Architects and the users of daylighting analysis, Researchers and Engineers, has widened further with recent advancements[8].

Common issues with building performance simulation tools, is that the tools are often considered "not compatible with Architects' working methods and needs"[8]. From the perspective of the Architect, simulation tools are considered, "cumbersome … and lacked user interfaces that were intuitive and easy to learn"[18] since they were developed for the purpose of analysis by Researchers, building Scientist and Engineers. As a result, the use of building performance simulation tools in architectural design and practice has been limited. To address this gap, the issue has to be shifted from the performance of the tools which thus far has been focused on data verification and analysis to the human-computer interaction component of the tools. In fact, accuracy and human computer interaction are not mutually exclusive since improvements in the human-computer interaction of the tools may lead to a reduction in errors and omissions leading to more consistent and accurate analysis results. Recognizing that architects are visually oriented professionals whose outcome is represented in the form of drawings, a careful analysis of the design process needs to be coupled with the evaluation of simulation tools to promote its use by design professionals.

1.2. Research Method - Overview

This research differentiates itself with the existing research on daylighting simulation tools based on its approach and method and builds upon a previous research by the author[21]. From the approach perspective, while the majority of previous research analyzed daylighting analysis tools based on accuracy, calculation

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method, among other factors which are beyond the scope of most architects; this research examines daylighting analysis tools from the perspective of its potential end user, the Architect. From the method perspective, daylighting analysis tools are evaluated based on a simple simulation task and its integration with the work-flow of existing CAD platforms (identified by architects from previous user surveys as key barriers that prevent its integration to design). The research method is visually represented in Fig. 1., Research Method.

1.3. Research Methodology – Integration Matrix

The research is divided into two main components. A review focusing on integration, and a review focusing on the tool itself. For the integration component, the work-flow of Architects from architectural CAD platforms to daylighting analysis tools are presented in a matrix. Past and present daylighting simulation tools are organized by release date, it's availability, and its type. The selection of tools were based on the following criteria:

- Daylight analysis tools released from 1979 to current are identified based on existing literature (reference is noted if applicable) and through a search of governmental and educational sources focusing on sustainable building design.
- Daylight analysis tools that analyze limited building elements were omitted (for example, Skycalc is a daylighting analysis tools for a specific building element, the skylight).
- Multiple releases / versions of the same tool are listed once based on their initial release date. In cases where subsequent versions include significant development that affect its ease of use (for example, a graphic user interface or plug-in), the software may be included twice (i.e. Radiance, and Desktop Radiance).

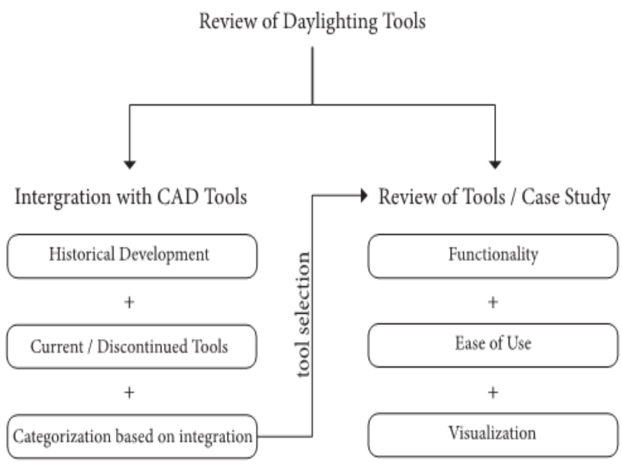
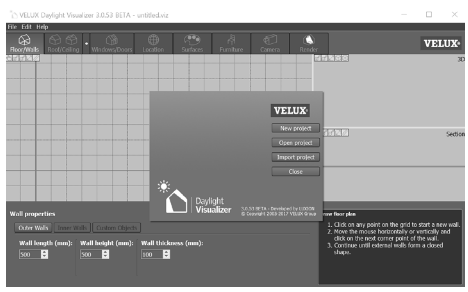
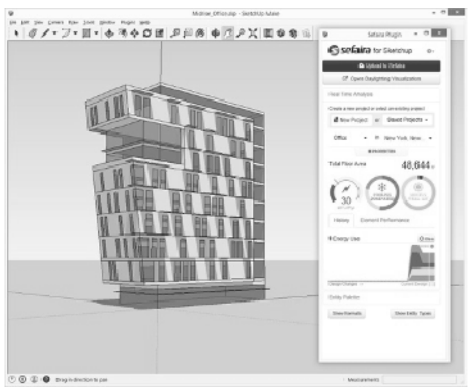


Fig. 1. Research Method

- Currently available and discontinued daylight analysis tools are graphically differentiated (discontinued tools are grayed out).
- Tools that include both energy and daylighting analysis have been included and identified in the matrix with an asterisk designation.
- Daylighting analysis and calculation tools without simulation components are identified and categorized in a separate column.
- Rendering tools without daylighting analysis capabilities are excluded from the matrix.

Once the analysis tools were identified, organized by release date, and differentiated between availability, the tools were first categorized based on their capability (analysis and simulation). Tools that included daylight simulation were further categorized based on the three types user interface: stand-alone software without a graphic user interface, stand-alone software with a graphic user interface, and plug-in to CAD drafting / modeling software. An illustration of the interface is represented in Table 1., Types of User Interface.

Table 1. Types of User Interface

Type	Graphic User Interface
Type 1: Stand-alone without Graphic User Interface	N/A
Type 2: Stand-alone with Graphic User Interface (Source: Velux 3.053 Beta, latest version)	
Type 3: Plug-in/ Sefaira Plug-in Interface for Sketchup (Source: Sefaira)	

1.4. Methodology – Review of Tool

Findings of the integration matrix is used to select three daylighting simulation tools available as plug-ins (DIVA for Rhinoceros, Autodesk Insight 360 for Revit, and Sefaira for Sketchup) to widely used architectural CAD platforms. The simulation tool are then evaluated based on three parameters, functionality, ease of use, and visualization. The three parameters (functionality, ease of use, and visualization) to review daylighting simulation tools were identified from existing literature.

The first category, functionality, is a common parameter used in the comparison of simulation tools[7,26]. In previous research, functionality was evaluated through the available metrics that the tools used in its analysis. From the perspective of Architects, metrics itself may not have an immediate impact on the design unless it is used as a basis for compliance of green building certification. As a result, compliance requirements and relevant metrics are used as a basis for the review of functionality.

In a user survey[27] by 187 participants, whom 38% consisted of architects and designers, a need for a more "intuitive" and "user friendly design" tool was concluded since the currently available tools were "too specific and complicated". In previous tool evaluations, ease of use was often determined by subjective judgements such as observations. To provide a more objective analysis, input parameters for a simple simulation task is used as a basis for evaluation over more subjective criteria.

In another survey by 249 architects and designers who evaluated ten building simulation tools[8], 22,9% noted that "graphical representation of output results" as a top priority in a simulation tools. In addition, Architects and Designers communicate through visual means such as drawings and physical models rather than numbers or figures. As a result, one of the parameters for evaluation is identified as visualization, where different simulation and analysis modes offered by the tools are identified and listed as a basis for comparison. A more in-depth explanation of each category is provided in sections 3.2,3.3, and 3.4 respectively.

To initiate the review of the tools, a simple daylight simulation task is performed utilizing a modeled space of a typical classroom space in Seoul, Korea (37.5665° N, 126.9780° E). The typical classroom main area of 63m² with dimensions of 7m (l) m x 9m (w) x 3m (h) for the main space is modeled and includes a 2m wide adjacent corridor, with a interior wall with a glazed interior window to bring in light, see Fig. 2. The main classroom includes a south facing window centered in the space with a Window to Wall Ratio (WWR) of 25% to bring in natural daylighting and a glazed window between the main classroom space and the adjacent corridor. In addition, North facing windows are introduced along the corridor. The classroom dimensions, orientation, and glazing amount is typical of a public educational institution in Korea. Surrounding context of the case study space was not considered and was omitted from the three-dimensional model. In addition, the modeled space was created in each of the native CAD platforms to avoid any issues of interoperability (import, export) and was utilized for daylighting simulation and analysis.

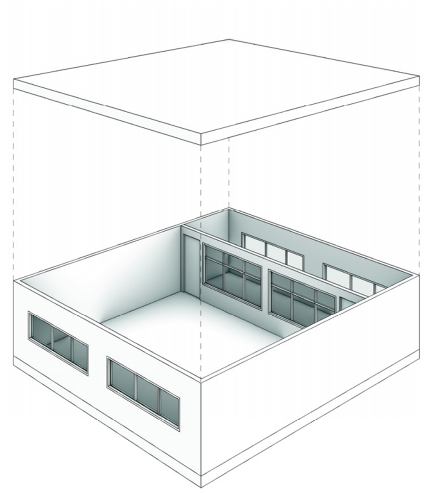


Fig. 2. Three-dimensional Model of a Typical Classroom Space

Simulation parameters include grid based illuminance sensors 12" apart at 0.85 m work-plane height. Electrical lighting was not considered and the simulation / analysis is based on calculating Daylight Factor. Optical surface properties are set as the default recommended values for each daylight simulation tool.

2. Theory

2.1. History of Computerized Daylighting Tools

The first developments of computerized daylighting calculation tools can be traced back to 1970 with Lumen-I which was developed by DiLaura for engineers to predict results of lighting design using point in space calculations[22]. Following Lumen-I, DiLaura subsequently developed Lumen-II, Lumen-III, Energy, leading to Lumen-Micro Version 1 in 1983. Meanwhile, other researchers and scientists have also been developing daylighting calculation tools including SUPERLITE and the daylighting module from DOE-2.1b from the Lawrence Berkeley Laboratory in 1982.

With the development of computer graphics (CG) came the next iteration of computerized daylighting tools. Using the backward raytracing method, researchers from the Lawrence Berkeley Laboratory developed Radiance in 1982. Radiance is a "physically based rendering system tailored to the demands of lighting design and architecture."[32]. The significance of Radiance is two-folds, first the daylighting simulation tool's intended audience has now included Architects and Designers and second its output has shifted from solely analysis to include visualization. As a result both the qualitative information (visualization) is coupled with the quantitative information (daylighting analysis / data). Even today, close to half of the existing daylighting simulation tools utilize the Radiance simulation engine1)[27] and the tool is still being actively used by Researchers and Professionals.

2.2. Daylight Simulation Engines

The main daylight simulation engines used in recent daylighting simulation tools include radiosity and ray-tracing, and most tools utilize both simulation engines in a hybrid approach. A brief description on the simulation engines is discussed below, but an in-depth review of these algorithms is beyond the scope of this research.

Ray-tracing algorithms were first developed by Foley, Whitted[10] with a primary purpose to generating images with "greater realism". Ray-tracing include two main types, forward and backwards ray-tracing and in both situations, rays of light are traced. Whitted describes forward ray-tracing approach as, "light rays emanating from a source are traced through their paths until they strike the viewer…"[10] Since the light rays are emanated in all directions from the source, the tracing of the rays are taxing and inefficient since only the rays that reach the viewer (image plane) are used to generate an image. In backward ray-tracing, developed in 1986 by Arvo[6], an opposite approach is taken, where light rays from the "viewer to the objects in the scene" are traced. Daylighting simulation tools that utilize raytracing simulation engines include Radiance, DIVA, Daysim among others.

Radiosity algorithms were first introduced by Gora1 et. al[13] based on the theory of heat transfer and applied to computer graphics. The radiosity algorithm "models the interaction of light between diffusely reflecting surfaces." In radiosity, surfaces in the environment become Lambertian reflectors (reflect incident light in all directions with equal intensity). Daylighting simulation tools that utilize radioisty algorithm include SUPERLITE, and RadioRay.

In a hybrid approach, both radiosity and ray-tracing algorithms are utilized within a single software tool. Utilizing the benefits of each method, radiosity is used to calculate interaction between diffuse surfaces while ray-tracing is utilized for calculation specular reflections within a simulation. An example of a daylighting simulation tool that incorporate both include Lightscape, and in an Architectural CAD platform 3D Studio Max incorporates a hybrid approach.

2.3. Review of Previous Studies

Existing research on daylight simulation tools can be categorized into three categories. First category of research pertains to the new development of tools, strategies [2, 20, 23] or daylighting metric. The second category of research includes the analysis and comparison of existing daylighting tools, mainly focused on comparing the accuracy of results amongst one another often with real-world measurements[1, 3, 15, 31]. The third category of research focuses on identifying current issues of daylighting simulation tools through user surveys often targeting a certain user group[8,26,27]. Existing literature in the first two category are aimed at researchers, building scientists, and engineers, while the third type of research covers a wide spectrum of professionals (Engineers and Designers). Since this research is based on the perspective of the Architect, examination of existing literature is performed on the third category of research to understand issues that deter or limit the use of daylighting simulation tools in architectural design.

Attia et al.[8] evaluated ten building simulation tools (Ecotect, Heed, Energy 10, Design Builder, eQuest, DOE-2, Green Building Studio, IESVE, Energy Plus, and Energy Plus-SketchUp Plugin (OpenStudio) from an "architectural perspective" to provide recommendations on the development of "architect friendly" simulation software. Online survey of 249 responses from Architects and Designers, excluding responses from Engineers and Researchers, were conducted. As part of the background, the survey identified commonly used CAD drawing / drafting and 3D modeling software. Findings include that respondents used more than one CAD software with the use of AutoCAD and Sketchup out numbering other software. However, no further links between CAD software and building performance simulation tools were identified and presented. Other findings include that architects considered graphical representation of output results (22.9%) and flexibility of use and navigation (17.3%) as top priorities in a building performance simulation tool. The research concludes with a need for a development of a "visual and interactive" building performance simulation tool for Architects.

Panitz & Garcia-Hansen[26] conducted a survey of architectural firms in Australia to identify and evaluate the daylighting simulation tools used by the industry based on "ease of use, efficiency, and outcomes". The research conducted a survey of the use of current CAD tools used for modeling and analysis. Survey results indicate that the most commonly used software for digital modeling are Sketchup and Revit which validated Attia et al's[4] earlier research. On the analysis side, the most commonly used analysis software includes 3DS Max, Ecotect, Sketchup with experimental Daysim Plug-in Su2ds and Diva with Rhinoceros.

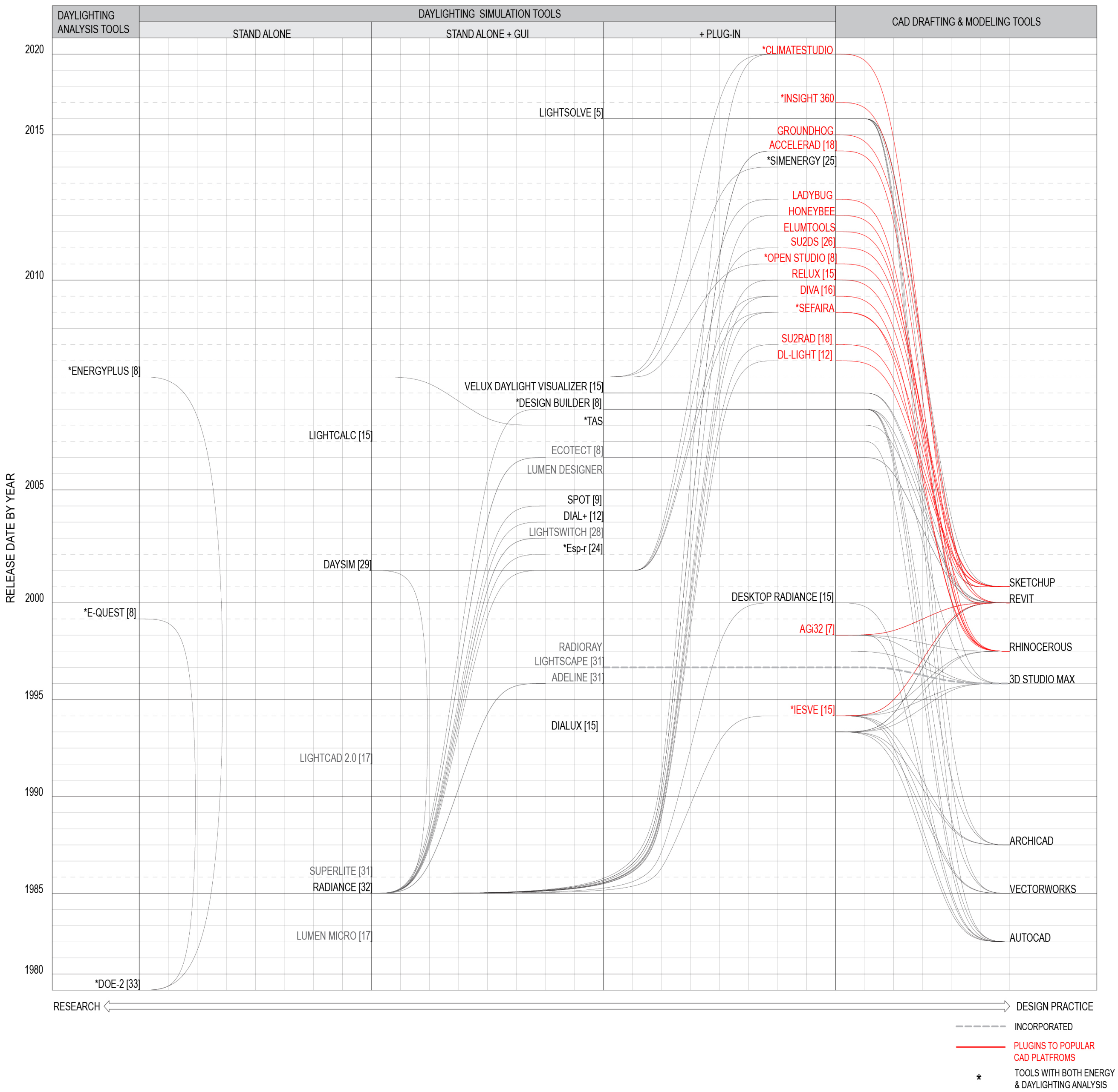


Fig. 3. Integration Matrix: Daylighting Simulation Tools and Architectural CAD Platforms

An evaluation of select software was performed based on "ease of use". Results indicate that "the most adaptable method for daylighting analysis within architectural practice at this point in time, is using programs that integrate effectively with current BIM based or modeling solutions…"[7]. Furthermore, the research noted the need for analysis software to be "easily integrated into the current work-flow of an Architect…"[7].

Reinhart & Fitz[27] performed a survey on the current use of daylight simulations to 187 professionals whom 38% consisted of Architects and Lighting Designers. The objective of the survey was "motivated by the authors' observation that despite the availability of simplified and detailed daylight simulation methods, none of these tools has yet penetrated the building design market to any great degree"[15]. Findings include that the primary barrier for not utilizing computer simulation tools is that the participants, "did not know which tools to use…" Other findings include the need for a more "intuitive" and "user friendly design" tools, since the currently available tools were too specific and complicated. The participants of the survey identified 42 different daylighting simulation tools with over 50% based on the Radiance engine.

Based on a review of existing literature focusing on user surveys, the following can be summarized:

1. Lack of Information: Architects are not aware of what tools

to use to perform a daylight simulation[15]. Even with a large number of available tools, information regarding the tools itself, its use, and compatibility with CAD drafting software that are familiar with Architects have not been presented in a manner that is informative or easy to comprehend.

2. Integration: Daylighting simulation tools need to integrate effectively with current architectural software and work-flow[7]. Existing literature points to the fact that the lack of integration between architectural modeling solutions and simulation tools exists.
3. Ease of Use / Visualization: The need for an intuitive, user-friendly[27], visual and interactive tool that is easy to use and navigate[8] was concluded from existing literature. The significance of graphical representation of the results[8] was also noted as an important factor.

This research attempts to address these three findings from existing literature by creating an integration matrix and a review of the daylight analysis tools. The integration matrix serves multiple purposes. Academically, it provides a historical overview of computerized daylighting simulation and analysis tools. In its application to practice, it provides information to aid in the selection of tools by illustrating the extent of integration with current Architectural modeling solutions. Finally, the matrix aims to provide background information in the development of future daylight simulation tools.

3. Integration Matrix

3.1. Daylighting Tools & CAD Tool Matrix

Approximately fifty daylighting analysis tools from 1979 to 2020 (past four decades) are identified based on the selection criteria outlined in section 1.3 Research Methodology. The tools were further evaluated and filtered resulting in a total of forty daylighting analysis tools being plotted onto a integration matrix. Along the Y axis, the matrix is organized first by a timeline in ascending order (from bottom to top, left hand side) based on their initial release date. In addition, popular architecture CAD platforms, identified through existing research, are also plotted based on their release date. Along the X axis, the Daylighting Tools are organized into four categories based on their software structure (analysis only, simulation stand-alone, simulation stand-alone with GUI, and simulation plug-in).

The relationships between the CAD platforms and the analysis tools are illustrated through a continuous line. The continuous line represents the work-flow of the Architect or Designer from the CAD platform to the simulation tools. Often this process requires export of the CAD model from one stand-along tool to another (for example, a three-dimensional model generated from McNeel Rhinoceros exported in obj format and imported in Velux Daylighting Visualizer to perform simulations and daylighting analysis). In instances where this work-flow is streamlined by the tool being offered as a plug-in to a specific or even multiple architectural CAD platforms, this line is emphasized with a color designation (for example Insight 360 to Revit).

The compiled Integration Matrix is shown in Fig. 3., Integration Matrix: Daylighting Analysis Tools and Architectural CAD Platforms. The purpose of this matrix is to understand the history of the daylighting simulation tools, the trends in development over time from the different types, but also aid in the selection of tools for Architects and Designers based on its integration with Architectural Modeling solution.

3.2. Review of Tool - Functionality

Recent trend in the development of daylighting analysis tools indicate that tools in the form of plug-ins are being developed for three main Architectural CAD platforms[2)]: Trimble Sketchup, Autodesk Revit and McNeel Rhinoceros. Tools developed in the past decade have been in the form of a plug-in[3)] to these three Architectural CAD platforms. Of the numerous plug-ins available, three widely known tools, Trimble Sefaira for Sketchup, Solemma DIVA for Rhinoceros and Autodesk Insight 360 for Revit, are selected to perform a simple simulation task and represented in Table 2.

The first criteria for evaluation is its functionality. Previous reviews of daylighting analysis tools have also reviewed the tool's capabilities to generate results based on daylighting metrics as a way to compare its functionality[7, 26]. However, from the perspective of the Architect, the output of results based on scientific metrics alone has limited use in practice. Instead, metrics used for the compliance of Green Building certifications and building codes would be more pertinent in design and is the basis for determining functionality. The following daylighting certification and code guidelines are reviewed, refer also to Table 2. Functionality of Daylighting Simulation Plug-ins:

1. Building Code, Metric Daylight Factor : Daylight code compliance has traditionally used Daylighting Factor is a daylighting metric and is still being used. However, in recent green building certification requirements this metric has been replaced by climate based metrics.

2. LEED v4 EQc7 (Option 1), Metric Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE):

Table 2. Functionality of Daylighting Simulation Plug-ins

	Compliance	Metric	Tools		
			Sefaira + Sketchup	DIVA + Rhino	Insight + Revit
Functionality	Building Codes	DF	●	●	●
	LEED v4 EQc7 (Option 1)	sDA	●	●	●
		ASE	●	●	●
	LEED v4 EQc7 (Option 2)	illuminance		●	●
	LEED 2009 addendum IEQ 8.1	illuminance		●	●
	SEPP 65 (Australia)	direct radiation	•		●
	NE-CHPS IEQ P2	cDA		●	
	MA-CHPS EQ C2	DA		●	

• with limitations

Demonstrate through annual computer simulations that spatial daylight autonomy300/50% (sDA300/50%) of at least 55%, 75%, or 90% is achieved. Use regularly occupied floor area. [38]

3. LEED v4 EQc7 (Option 2), Metric Illuminance: Demonstrate through computer modeling that illuminance levels will be between 300 lux and 3,000 lux for 9 a.m. and 3 p.m., both on a clear-sky day at the equinox, for the floor area indicated in Table 2. Use regularly occupied floor area. [38]

4. LEED 2009 IEQ 8.1, Metric Illuminance: Demonstrate through computer simulations that the applicable spaces achieve daylight illuminance levels of a minimum of 10 footcandles (fc) and a maximum of 500 fc in a clear-sky condition on September 21 at 9 a.m. and 3 p.m. [38]

5. SEPP 65, Metric Direct Solar Radiation: Living rooms and private open spaces of at least 70% of apartments in a building receive a minimum of 2 hours direct sunlight between 9 am and 3 pm at mid winter in the Sydney Metropolitan Area and in the Newcastle and Wollongong local government areas. [37]

6. NE-CHPS (Northeast Collaborative for High Performance Schools), Metric Continuous Daylight Autonomy also known as Daylight Saturation Percentage (DSP) or Spatial Daylight Saturation (sDS) : Achieve >60% sDS400/50%. [34]

7. MA-CHPS (Massachusetts Collaborative for High Performance Schools) EQ C2, Metric Daylight Autonomy (DA): For all classroom spaces achieve >40 -80% DA for >50-75% occupied area (points vary from 1 - 4 points) [35]

3.3. Review of Tool – Ease of Use based on User Input

The second criteria for evaluation is "Ease of Use". Ease of use is often a subjective criteria that varies greatly depending on a wide number of factors including the user's experience and expertise in navigating computerized tools. In existing literature comparing different building simulation tools, ease of use was determined, "via observation of legibility / output, speed, ease of use, and importing / exporting data capability…"[21]. In the perspective of a Design Professional, whose familiarity with simulation tools may be limited, ease of use can be determined by reviewing the required input parameters in completing a basic daylighting simulation task, see Fig. 2.

To initiate a daylighting simulation, weather data, geometry, material properties, and simulation settings needs to be defined. Since geometry is provided by the architectural tool, ease of use will determined based on the remaining required input parameters (weather data, material properties, simulation settings). In Table 3. Ease of Use based on User Input, categories are reviewed based on the available options and its extent of customization. For some parameters, users can self-define the parameter (user defined), input based on a pre-determined selection (limited selection), or in cases where user input is disallowed, the program defined settings area automatically applied (program defined).

3.4. Review of Tool – Simulation / Analysis Modes

The third criteria for evaluation of tools is visualization. Under the general term visualization, a distinction is made between daylighting simulation and analysis for each type of visualization mode. In existing user surveys[8], Architects considered "graphical representation of output results" as an important factor in the selection of Building Performance Simulation tools. To address this finding in the review of tools, different visualization modes offered are presented in Table 4. For each category or type, the view type (perspective, fisheye) and the type of analysis is described. A brief description for each type of visualization is below.

1. Point in time Illumination – Illumination levels in a point in time, space and location is simulated and analyzed. Illuminance levels in lux is shown using a false color map with a gradient of illuminance levels.

Table 3. Ease of Use based on User Input

	Required Input	Tools		
		Sefaira + Sketchup	DIVA + Rhino	Insight + Revit
	Weather Data	by location	user defined, by file	by location
Material	glass	user defined	limited selection	user defined
Material	other materials	program defined	limited selection, custom settings through advanced settings	user defined
Simulation Settings	Sky Model	- CIE Overcast - Perez	- CIE Overcast - CIE Intermediate - CIE Clear - Perez - Uniform - Utah Colored Sky Model - Intermediate Sky with Sun	- CIE Overcast - CIE Intermediate - CIE Clear - CIE Uniform - Daylight Factor Sky
Simulation Settings	Grid Sensor Spacing	limited selection	user defined	limited selection
Simulation Settings	Simulation Engine Settings	program default, only ambient bounces can be adjusted	user defined	program defined

2. Annual – A category that encompasses a wide range of annual daylight simulation and analysis including climate based metrics such as daylight autonomy (DA), spatial daylight autonomy (sDA), and annual solar exposure (ASE).

3. Glare – Glare simulation and analysis is inclusive of both a point in time glare simulation and an annual glare analysis. Results are shown using metric[4] known as Daylight Glare Probability (DGP).

4. Results

4.1. Findings from the Matrix

Reviewing the Integration Matrix (Fig. 3.), a few interesting developments can be identified. First, daylighting analysis tools in the form of plug-ins have been focused on integration with three existing mainstream CAD platforms, Trimble Sketchup, McNeel Rhinoceros, and Autodesk Revit. For example, GroundHog developed in 2015 is a radiance-based daylighting simulation tool available as a plug-in exclusively for Sketchup. Likewise, Accelerad developed in 2014[5] is a radiance based daylighting analysis tool exclusively available as a plug-in for Rhinoceros.

Table 4. Visualization Modes

	Type		Tools		
			Sefaira + Sketchup	DIVA + Rhino	Insight + Revit
Visualization	Point in Time	Simulation	Perspective	- Perspective	Perspective
Visualization	Point in Time	Analysis	False Color Map	False Color Map with point designation of illuminance	False Color Map
Visualization	Annual	Simulation	Perspective	- Perspective - 80 Fisheye	Perspective
Visualization	Annual	Analysis	Summary	Daysim Simulation Report	Summary
Visualization	Glare	Simulation	-	- Perspective - 180 Fisheye	-
Visualization	Glare	Analysis	-	Annual Glare Report	-

Second, since 2008, a shift in the type of daylighting analysis software occurs from stand-alone tools to plug-ins, see Fig. 4. Historical Development of Daylighting Tools. With the exception of Lightsolve (2016) & Sefaira (2009), which are both available as a stand-alone tool and plug-ins, all analysis tools have been developed exclusively as plug-ins with the majority based on Radiance. Prior to 2008, the analysis tools were pre-dominantly stand-alone programs with its own dedicated graphic user interface capable of accepting a wide format of files from popular CAD platforms. Of the forty tools plotted on the Integration Matrix (Fig. 3.) starting from 1979, eighteen tools are offered as plug-ins and twenty three tools are offered as stand-alone tools of which nine are currently discontinued.

Third, CAD software platforms have started to incorporate functionality of existing daylighting simulation tools into their own software. Autodesk has discontinued Ecotect Analysis and has started to migrate its functionality into Revit and Insight 360, and Lightscape was integrated into Autodesk VIZ 4.

4.2. Analyzing the Daylight Simulation Tool

Three daylighting simulation tools in the form of plug-ins were reviewed based on functionality, ease of use, and visualization modes based on a simple simulation task.

A review of functionality focused on the tool's ability to simulate and analyze metrics that are required for compliance of green building standards and code. Of the three plug-ins reviewed, DIVA was able to simulate a wide variety of metrics that

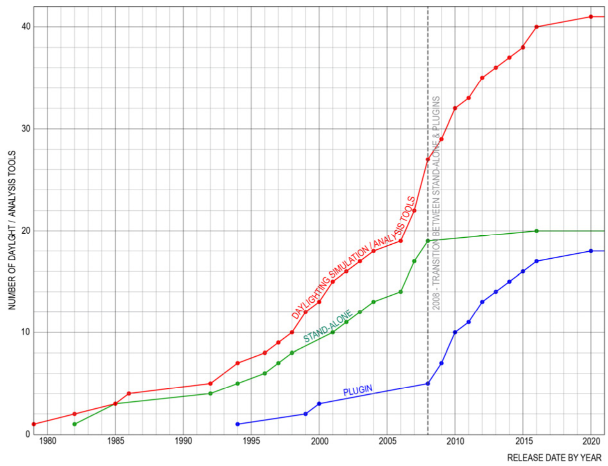


Fig. 4. Historical Development of Daylighting Tools

are used as the basis for both national green building standards (LEED) but also local green building standards for specific building types (CHPSA).

A review of ease of use focused on the input parameters (weather, material properties, simulation settings) required to perform a simulation task. Compared to Sefaira or Insight, DIVA provided the most flexibility by allowing users to define input parameters including a wide range of sky models and the ability to customize Radiance settings[5] which were not available in Sefaira.

A review of tool's visualization modes was evaluated based on the tool's ability to provide both simulation and analysis information. Sefaira and Insight lacked the capability to simulate and analyze Glare, while DIVA provided the most types of visualization modes and camera views. Also, the three software differed in the way in which analysis information was presented. Sefaira provided brief description of the results which DIVA provided analysis in terms of a chart and report. Insight also provided analysis of results in a web based format.

In addition to the analysis of the tools itself, an interesting aspect that aids in the development of the tools is that both the CAD application and Daylighting Simulation Tools are being developed by a single Architecture Engineer Construction (AEC) company. For instance, Sefaira and Sketchup is both owned by Trimble (Trimble acquired Sefaira in 2016) while Autodesk develops both the Insight 360 plugin and Revit. This may lead to better interoperability, consistency in both the graphical representation and the graphic user interface that may be difficult to achieve with other plug-ins developed by separate companies.

4.3. Limitations of Research

While considerable efforts has been made to cover the majority of daylighting analysis tools developed since 1979, there may be errors and omissions in the integration matrix. One of the main reasons for errors and omission are due to the fact that most tools are not developed by the Architecture Engineer Construction (AEC) industry but are developed by Researchers and Scientists for the purposes of academic research. This often leads to software being discontinued after the completion of the research which prevents data collection and evaluation of the tool. As a result, the data gathered for the integration matrix relies on published research whose intended purpose may not be focused on the tools itself. On the opposite site of the spectrum, tools that have been updated frequently and are currently available for evaluation, are also limited due to the fact that previous versions of the software are often unavailable. This also prevents evaluation of previous versions to determine updates and changes over its course of development.

Comparative evaluation of daylighting simulation tools are often limited due to the subjective nature of the evaluation criteria. This research attempts to alleviate the subjectiveness by identifying criteria that are quantifiable such as metrics and input parameters. As a result, information is presented and organized without a clear conclusion. This is both the strength and weakness of this comparative approach.

5. Conclusion

This study evaluates daylighting analysis tools from the perspective of architectural design and based on integration with currently available architectural tools. The Integration Matrix (Fig. 3.) generated provides valuable information to Architects and Designers in the selection of computerized daylighting analysis tools based on their own expertise and proficiency of existing architectural tools and their work-flow. In addition, it presents trends in the development of tools based on a historical overview of the past four decades. In terms of the actual tool itself, three daylight simulation tools are evaluated in based on its functionality, ease of use, and visualization. The information collected may aid in the development of the next generation of simulation tools whose interface is more interactive and intuitive. As tools become more seamless integrated with the work-flow of Architects, simulation and evidence based design may be adopted by more Design Professionals. This research attempts to provide a small contribution towards that trajectory.

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1) Fig. 3. Integration Matrix, also represents the reliance of recent tools on Radiance and validates findings from previous research.
2) Version of software include Sketchup Pro 2020, Rhinoceros Version 6, Revit 2020.
3) Version of plug-in include DIVA version 4.0, Insight Lighting Analysis for Revit 2020, Sefaira latest release 2018.8.
4) Annual Sun Exposure (ASE) is often referred as a measure to evaluate glare but falls short of an evaluation of glare as a metric.
5) Under advanced parameters, users are able to customize radiance settings.