VISUALISING DAYLIGHT FOR DESIGNING OPTIMUM OPENINGS IN TROPICAL CONTEXT

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Published: 2024-04-30
Submitted: 2023-10-06
Accepted: 2024-04-22

ARSNET, 2024, Vol. 4, No. 1, 72-85
DOI: 10.7454/*arsnet.v4i1.87*
ISSN 2777-0710 *(online)*
ISSN 2777-0702 *(print)*

Abstract

With the rising concern for global warming, reducing electricity consumption and promoting daylight utilisation for healthier living conditions are among residential buildings' top priorities. The utilisation of natural light for indoor lighting, particularly in tropical countries like Indonesia, provides health benefits and improves psychological well-being. However, the current condition shows that artificial lighting still accounts for the majority of energy consumption in residential buildings and, arguably, the failure to maximise daylighting was largely due to a limited understanding of the design of openings. This paper aims to exemplify how virtualisation can assist designers through simulation tools to better predict and analyse daylight behaviour in indoor conditions through openings, which are oftentimes neglected by designers. Despite technical challenges, such 3D simulations of daylight visualisation can help to determine the best opening strategy. Thus, this paper compares three lighting simulation tools—Dynamic Daylighting, VELUX Daylight Visualizer, and Rhinoceros Grasshopper, showing the optimal visualisation of lighting quality for tropical context. Based on the model's accuracy as well as input quality and output analysis, the simulation tools are examined for their practicality and detailed daylight 3D visualisation output. This study demonstrates how the simulations of daylight visualisation inform not only the visual image of the window design, but also crucial parameters for designing openings. The parameters enable precise quality of simulation, elaborating the optimum design for performance required in tropical context.

Keywords: virtualisation, daylighting simulation, visualisation, tropical climate, residential architecture

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Introduction

The presence of natural light and its utilisation become an essential component of any building, promoting a healthy and sustainable living environment (Altomonte et al., 2017; Kubba, 2012; Wong, 2017). Daylighting refers to the diffuse natural light that fills an area during the day, improving not only the aesthetic of the space and architecture but also benefitting inhabitants' well-being. For tropical contexts like Indonesia, designing buildings with daylight in mind might be the best solution. As a tropical country with a year-round sunny climate (Edmonds & Greeup, 2002), the sky condition from the Equator to the Tropics is primarily bright and overcast (Chirarattananon et al., 1996), allowing the optimal use of natural light for indoor conditions.

Despite the advantages, the presence of natural light and indoor quality is often negotiated, resulting from the poor design of openings—size and the position of the openings, budget constraints, as well as overdependency of artificial lighting. Such phenomena are common in Indonesia, where the openings of buildings are less considered for a lower construction cost and better selling price. This condition generates dark interior conditions, particularly for long and narrow buildings. It leads to a high consumption of electricity, contributing to the residential buildings' energy consumption which rises significantly due to the high utilisations of artificial lighting (Akil et al., 2020; McNeil et al., 2019; Surahman et al., 2017).

On the other hand, large windows in tropical climates can also generate heating and the need for improved ventilation and extensive air conditioning, leading to further electricity consumption. Most designers assumed that large windows would allow for more daylighting (Mardaljevic, 2021). Different lights can produce significantly different amounts of heat at the same lighting intensity. Direct sunlight is not a suitable light source for indoor illumination, due to the gained heat. The primary purpose of having indoor daylighting is to create diffuse light from the sky to enter the building while preventing direct sunlight from entering. Thus, some challenges need to be calculated to create such indoor quality, including moderating the effect of direct sunlight in the interior condition and calculating the sky conditions due to clouds which severely fluctuate throughout the year.

To gain the maximum benefits from daylighting, the use of both natural and artificial lighting sources should be integrated at the design stage. According to Badan Standardisasi Nasional (2000) or the Indonesian National Standard on energy conservation of lighting systems in buildings (SNI 03-6197-2000), there are several factors to consider when planning and evaluating indoor daylighting conditions, as different requirements are needed for different functions. It is important to consider daylight in building design to minimise artificial lighting during the day.

The current advancement of technology allows digital tools for simulation in architectural design. A lighting simulation software program provides an accurate simulation of the lighting of a building (Kubba, 2012; Ward et al., 2022). It offers great potential for earlier analyses and simulations. Various options in lighting simulation software are available in the built environment can make designers choose the most appropriate software, as simulating on a computer requires more time and differing levels of knowledge and skills. Architects, especially those in Indonesia, tend to focus more on design than calculation, thus choosing 3D simulation tools that are close to reality and important in creating the best daylight visualisations. This paper explores the potential of different lighting simulation tools to simulate lighting quality for daylight in tropical climates with a focus on detailed daylight 3D visualisation, aiming to provide an overview and analysis of current lighting simulation tools with a simple case study. It is intended that the lighting simulation software can predict daylight analysis and help architects or designers make smart design decisions for their buildings.

Daylight-based simulation

Simulations are widely used in assessing passive systems (Toroxel & Silva, 2024). In the process of designing, dynamic simulation programs driven by climatic data can assist decision-makers (Toroxel & Silva, 2024). An in-depth analysis of the local climate is necessary before choosing an optimal opening design. Due to its proximity to the equator, Indonesia has less variation in temperature from season to season and has a temperature average of 28 °C in the coastal area experiences, 26 °C inland, and 23 °C in the higher mountain areas experience (Badan Meteorologi, Klimatologi, dan Geofisika, n.d.).

Even with simulation tools, predicting daylight was challenging. Natural daylight has varying intensities and colour compositions, influenced by solar positions and sky conditions (Müeller, 2013). It is daylight that determines luminosity and colour composition, as well as human perception and evaluation of the built environment (Müeller, 2013). Light from the sun strikes the earth's surface and the amount of diffused light that is seen depends on the intensity of atmospheric conditions as well as daily and annual cycles of movement (Müeller, 2013; Wong, 2017).

Visualising internal spaces before construction can be an aid for designing openings in residential buildings (i.e., in determining the window's location and size for improved daylighting performance). Natural lighting can result in unwanted solar heat gains for indoor conditions, meanwhile, efficient shading can cause a darker room condition, thus, fluorescent lighting becomes necessary (Altomonte et al., 2017; Müeller, 2013). Several systems including daylighting and solar control, diffuse skylight transmission, direct sunlight redirection, light scattering, and light transport should be calculated as well to avoid poor design (Ruck et al., 2000). Natural lighting and electrical lighting calculations should be integrated into the package as part of the simulation, as well as a thermal assessment of the impact of window design (Kubba, 2012; Wong, 2017).

As an important aspect of daylight visualisation, daylight factor (DF) is a measure of daylight availability in a room (Kubba, 2012; Mardaljevic, 2021; Wong, 2017), implying that a higher DF score, the more natural light is available in the room. The daylight quality is assessed by calculating the average daylight factor (Kubba, 2012), particularly in an obstructed setting (Mardaljevic, 2021). The DF can be expressed as below (Kubba, 2012; Mardaljevic, 2021; Wong, 2017), where Ein is defined as the ratio of the internal illuminance and Eext is the outside or external illuminance condition under a uniform or overcast sky (Equation 1).

$$DF = \frac{E_{in}}{E_{ext}} x\ 100\% \qquad (1)$$

The calculation of the DF using traditional methods can be particularly challenging, while in a computer-based calculation using simulation tools, DF or lux levels are automatically calculated based on a given static external condition using simulation (Wong, 2017). The output reflects the average daylight factor calculated from successive points on a working plane, rather than the average daylight factor over all surfaces (Kubba, 2012). Thus, the employment of simulation tools is considered very easy to use. This makes computational visualisation provides a strong basis for the design process (Christakou & Silva, 2008). An example of how a simulation tool was used to determine the best strategies for reducing glare and maximising daylight, a daylight simulation can be calculated on four different dates throughout the year, 21 January, 21 June, 21 September, and 21 December, aiming for a better strategy in reducing glare (Sari & Laksana, 2020).

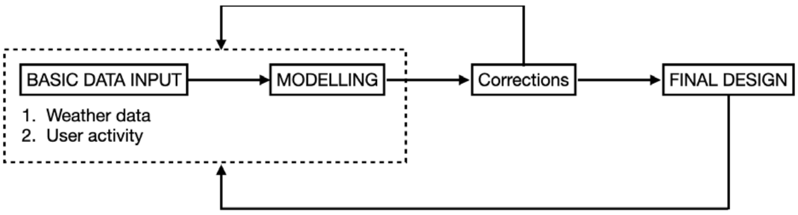


Figure 1. Framework for daylighting analysis of buildings (Image by author)

Recent technological advancements have enabled daylight design to advance. Currently, such advancements provide information that might meet all of the requirements of daylight consultants, architects, and end users (Kubba, 2012), despite some highly validated simulation software having complex calculations, lacking user-friendly interfaces, and incomplete manuals (Christakou & Silva, 2008). Figure 1 illustrates the possible iterative process of utilising daylighting modelling, starting with basic data input, modelling, corrections, and finding the final design, which can be the input for further process. The data in this framework was the minimum data input to the simulation tools. To utilise more complex and detailed software, additional inputs were required, such as the physical properties of the model space (ceiling, floor, wall, window, and roof) (Chang et al., 2020; Wong, 2017). It is possible for building energy models' parameters to be corrected depending on the amount of information available. In doing the simulation, it is reasonable to use the default settings if they are used solely for comparing different building parameters or conditions while controlling the detailed information (Chang et al., 2020) since the attempts to do simulations may not be perfect and their results can be inaccurate.

This paper explores the computational simulation of daylight applied to architectural design through the evaluation of three simulation programs—Dynamic Daylighting, VELUX Daylight Visualizer, and Rhinoceros Grasshopper. Three simulation programs were selected based on a quick survey among the students at Universitas Diponegoro, Semarang, Indonesia, based on their familiarity in utilising the programs. Through the analysis and evaluation of the tools following the architect's perspective, this research aims to provide a better understanding of the computational simulation of daylight.

Methodology

A description of the research framework can be found in Figure 2, starting from selecting a case study, comparing simulation using the simulation tools, and analysing the output from the simulation based on the quality of the generated 3D model and the model's accuracy. In particular, this study focuses on Jakarta, Indonesia as the context for daylighting simulation.

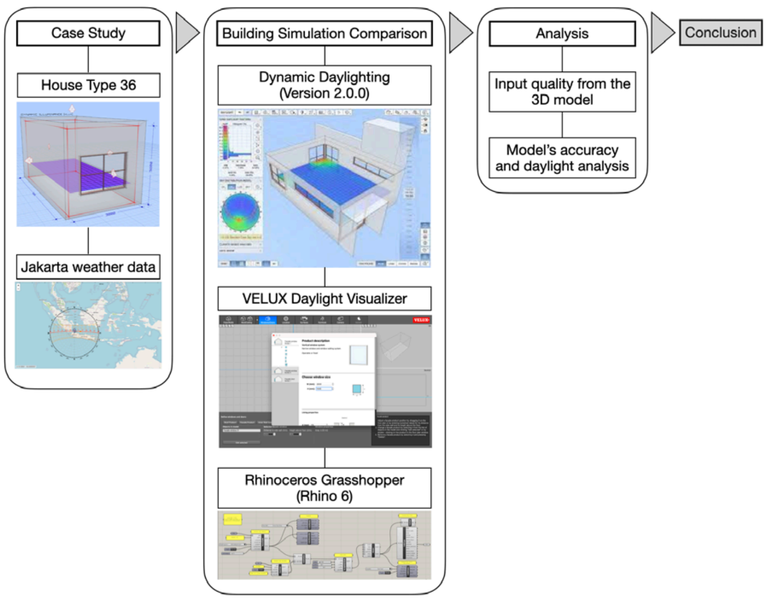


Figure 2. A framework for comparison simulation tools focused on daylighting (Image by author)

A typical house with a floor area of 36 sqm in Jakarta, Indonesia (6.1944° S, 106.8229° E) with a south orientation, is used for a case study in this study (Figure 3). The house type is popular in Jakarta, Indonesia, especially among newlywed couples, thus used for the case study (Sari et al., 2024). It usually only has one opening as the source of light at the entrance. This research focused on the house type-36 which is simplified to make more accurate daylight calculations. The model is rectangular-shaped with 6 x 3 metres in length and width and a floor-to-ceiling height is 3.20 metres. The central window of the house has the size of 1.45 metres (height) by 2 metres (width). However, the window shapes may vary among each simulation tool depending on its performance.

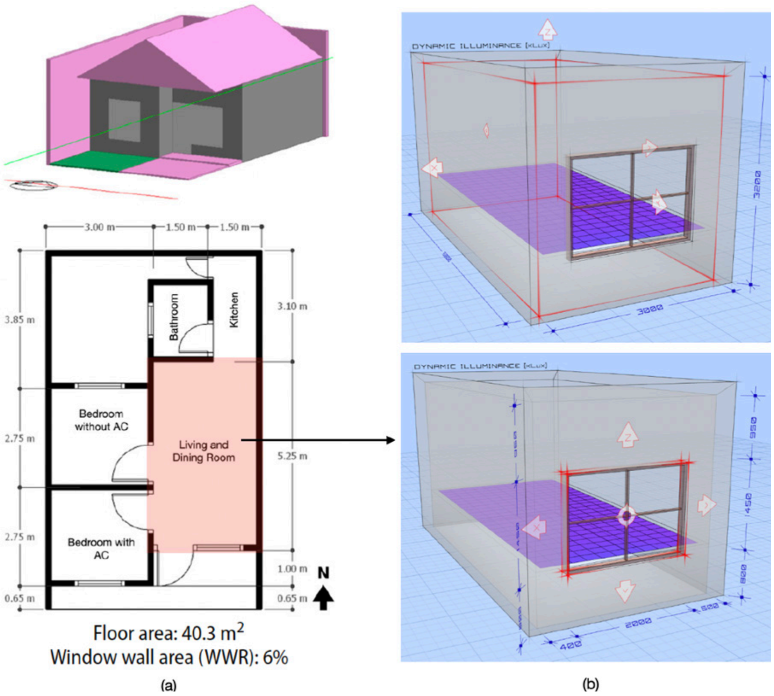


Figure 3. A simplified version of a living room in house type-36 (left) and the 3D model of the room for daylighting simulation testing (right) (Images by author)

This study evaluates three simulation tools: Dynamic Daylighting (Version 2.0.0) (Marsh, 2019), VELUX Daylight Visualizer (VELUX BIM & Building Visualization Tools, 2022), and Rhinoceros Grasshopper (Rhino 6) (Rhino, n.d.). Dynamic Daylighting is an open-source software that can be utilised online for free. Among architecture students at Universitas Diponegoro, it is the most popular software, easy to use, and on the other hand, it dynamically models the relationship between the spatial distribution of daylight in a room and its size, aperture configuration, shading devices, and external obstructions (Marsh, 2019). The tool provides optimised calculations with interesting 3D visualisation, making the procedure fast, responsive, and close to real-time daylighting updates.

The second simulation tool to be analysed is the VELUX Daylight Visualizer. This tool allows the possibility to inform decisions about daylight simulations for both small and large projects (VELUX BIM & Building Visualization Tools, 2022). In this simulation tool, the optimisation of daylight conditions is shown by photorealistic visualisations and false-colour mapping for standard and complex fenestration systems.

The next evaluated simulation tool is the Rhinoceros Grasshopper. Grasshopper for Rhino has two environmental analysis plugins, Ladybug and Honeybee, which are used for daylight analysis. Rhino requires a license, unlike the previous two simulation tools. In addition, the plugin was free of charge. As soon as Ladybug and Honeybee are installed and working, an interactive diagram will be displayed quickly and easily (Rhino, n.d.). The plugins include many diagrams by default, but it is also possible to generate geometry that allows better diagramming and design.

Afterwards, each software package is analysed based on the quality of the 3D model input and the accuracy of the model, which are important criteria for the users, particularly the architects. As part of a larger study, the lighting analysis is part of a method to position lighting system design in an increasingly value-driven construction method. The method will optimise building value for clients, developers, tenants, and users, ensuring good lighting quality in a value-driven design process.

Result and discussion

A simulation was conducted to determine each software performance's advantages and disadvantages, following descriptions of each simulation tool comparison. As mentioned before, the process and the output generated from the simulations are examined based on two aspects—the input quality from the 3D model and the accuracy of the model and daylight analysis.

Input quality from the 3D model

The comparison of the 3D models for each program is illustrated in Figure 4. There is no internal obstruction in the geometric model used in dynamic daylighting, but any number of rectangular windows and wall thickness can be selected to suit the needs of the situation (Figure 4a).

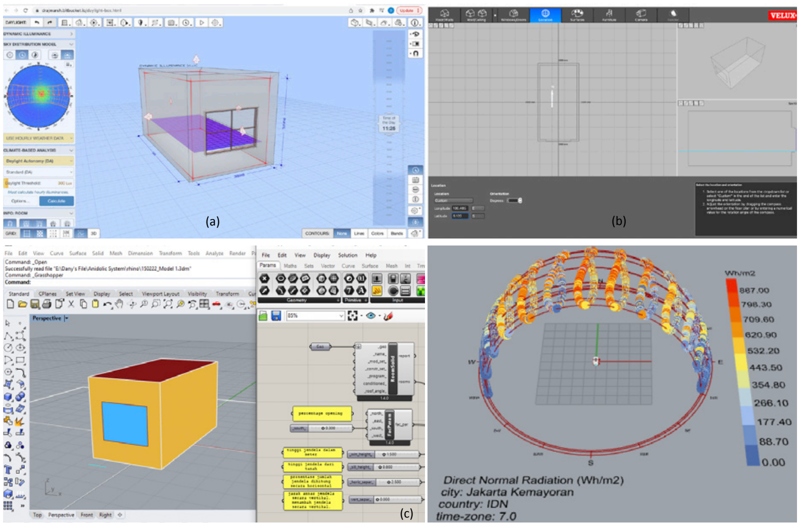


Figure 4. Comparison of the geometric 3D model created using (a) Dynamic Daylighting, (b) VELUX Daylight Visualizer, and (c) Rhinoceros Grasshopper (Image by author)

Dynamic Daylighting examined an optimisation strategy for daylight analysis and study (Figure 5), importing a 3D model from SketchUp. For the simulation, a simple rectangular plan shape was chosen for the initial implementation because simple daylight analysis methods work well with an axially aligned plan (Marsh & Stravoravdis, 2017). Custom widths and depths of window frames are available, as well as mullions and transoms of any length. The software can manipulate window frames, surface reflectance, and glazing transmittance. The placement of the analysis can be adjusted with ease while changing the room size or the window configuration. It nevertheless limits the model to a simple rectangular room with axially aligned rectangular windows on each wall, as well as cuboid shading devices and external obstructions.

Compared with the previous simulation tools, VELUX Daylight Visualizer also features easy-to-use 3D modellers that can be used to sketch a wide variety of room types within a few minutes (Foldbjerg et al., 2022). The software can generate a variety of simple 3D models including windows and roofs within minutes, employing Revit, Archicad, Autocad, SketchUp, and Rhino as a source of fully detailed 3D models. The simulation focuses on residential analysis and thus, the model will rely on rectangular shapes (Figure 4b). Real-world window products can be included in the model by dragging them onto the roof or walls and arranging them in a desired location. Compared to Dynamic Daylighting, VELUX has more options when it comes to designing window alternatives, such as roof-based openings. VELUX can visualise luminance, illuminance, and daylight factor levels. A setting in the interior camera setting allows to selection of particular daylight conditions and generates plan views, section views, and perspective renderings. As well as sunlight redirection, this model can also be used to simulate the installation of light pipes, blinds, and light shelves.

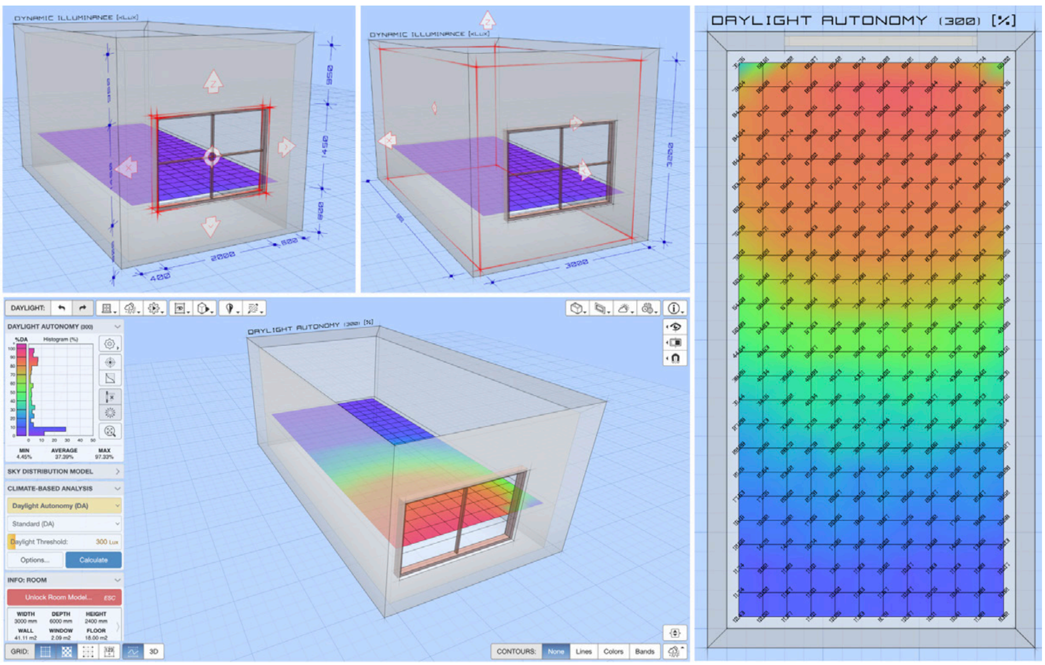


Figure 5. The utilisation of Dynamic Daylighting shows that daylight is distributed over a rectangular-shaped floor surface (Image by author)

Rhinoceros Grasshopper is widely used in architectural design companies because it is capable of creating complex and continuously evolving forms (Chirarattananon et al., 1996). With Grasshopper, it can generate parametric models quickly using a graphical language (Sari & Laksana, 2020) as it provides various 3D modelling features and has a flexible interface. With parametric daylighting analysis, early design stage lighting analysis will be more accurate. The software allows for the creation and modification of models simultaneously. Grasshopper and Rhino geometry are combined with open-source EnergyPlus Weather (EPW) data to produce site-specific climate analysis graphics. The Honeybee software links the geometry of Rhino and the functionality of Grasshopper to several advanced energy modelling and simulation tools such as Radiance, Daysim, EnergyPlus, OpenStudio, and gbXML.

As a result, both the Dynamic Daylighting and VELUX Daylighting Visualizer versions' 3D models are only capable of representing a simple rectangular building (Figure 6). Additionally, the Daylighting Visualizer can be used on all devices without installation, is easy to use, and fast. Considering that windows are the main component of daylighting, the VELUX Daylighting Visualizer shows more detailed window models than Dynamic Daylighting. A Rhinoceros Grasshopper simulation tool offers more flexibility than the other two, allowing architects to design complex designs with multiple variations.

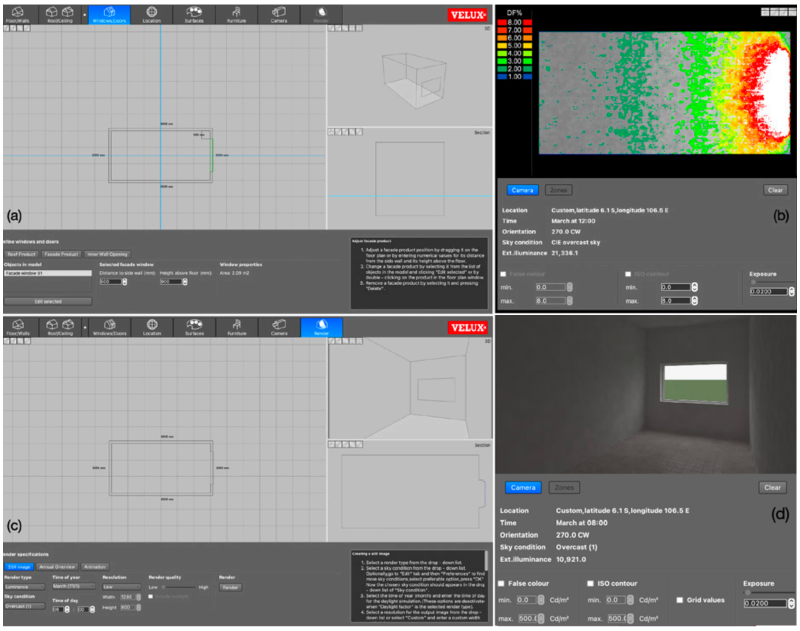
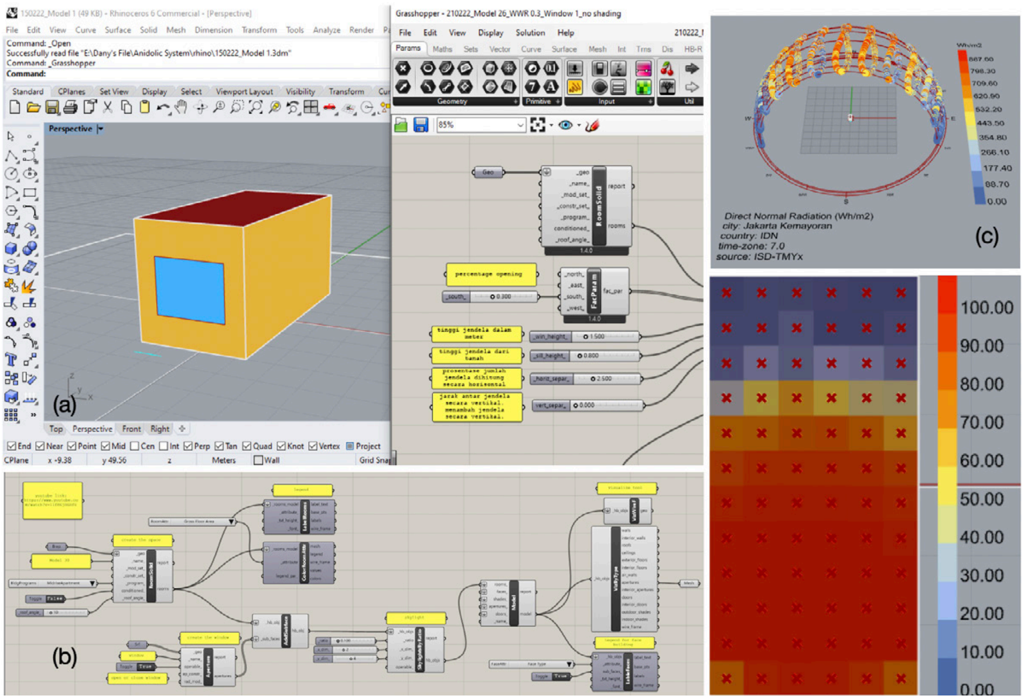


Figure 6. Daylight analysis results using VELUX Daylight Visualizer (Image by author)

Model's accuracy and daylight analysis

In the case of Dynamic Daylighting, daylight was calculated with a split-flux model and validated with Radiance. It can easily show the daylight distribution in real-time as it manipulates the calculation parameters dynamically. By inputting the information provided by the prototype, users will be able to assess the relationships between daylight distribution, the dimensions of a space, its surface properties, the size of a window, and its location concerning other variables (Marsh & Stravoravdis, 2017). When used with a relatively simple rectangular model, it is also shown that the process of computing spatial daylight distributions can be optimised so well that it becomes largely irrelevant when updating animation frames. However, the simulation using Dynamic Daylighting is limited to simple rectangular rooms and it does not specify which standard should be used to validate the daylight analysis although it will be useful for designing openings of new projects early on.

The daylight analysis which was generated using VELUX Daylight Visualizer provides information through plan, perspective, and top view. At the same time, it shows the analytical result based on DF percentage. Since the location of the weather data is not specific, it can only be input using longitude and latitude, but still possible to check the drawing of the window size and position as well as the 3D rendering result through illuminance and luminance. The Monte Carlo ray tracing with photon mapping is used in VELUX Daylight Visualizer to perform simulations. Materials used for surface properties and surface materials are described by Fresnel equations, which include plastic, metal, and glass. Test cases for assessing lighting computer program accuracy in CIE 171:2006 were used to validate daylight visualisation calculations (Foldbjerg et al., 2022).



In this case, VELUX Daylight Visualizer accurately predicted daylight levels and the appearance of a space lit by daylight in all cases, and the average error was less than 1.63% in all cases. The VELUX Daylight Visualizer can simulate luminance, illumination, and DF. Daylight calculations are made using any of the 15 CIE sky descriptions. When viewing simulation results in the output viewer, images are mapped with false colour or contour lines. Results from luminance and illuminance analyses of 3D renders are realistic. Compared to Dynamic Daylighting, this simulation tool is more comprehensive. However, one of the weaknesses of this tool is the limited input data acquired for the weather data. It can only input latitude and longitude data. Any other format including EnergyPlus Weather or EPW file cannot be opened. The main purpose of the VELUX Daylight Visualizer provides accurate and accessible simulation tools for evaluating

Figure 7. Daylight analysis results using Rhinoceros Grasshopper (Image by author)

indoor air quality in homes. This tool is primarily recommended for simulating simple one-level buildings.

The Rhinoceros Grasshopper programs offer parametric optimisation methods (Rhino, n.d.). To analyse lighting, Grasshoppers should connect with plug-in programs such as Ladybug and Honeybee. Ladybug provides a lot of useful features to assist designers in the early stages (Rhino, n.d.). It allows the designer to import EPW files and provides a range of 3D interactive graphics or metrics such as sunpath, wind-rose, radiation roses, radiation analysis, shadow studies, and view analysis (Figure 7). It shows that the parametric model can be easily modified with Grasshopper. As a result, these programs can calculate lighting data such as daylight autonomy (DA). DA is a method of evaluating the daylight quality of any given hour, geographic location, and sky condition on an annual basis (Figure 7b). In this case, the daylighting analysis also shows how exterior and interior analysis include daylight autonomy (Figure 7c).

Honeybee helps dig deeper and provides a more nuanced analysis. Honeybee has interfaces to five analysis engines: Radiance for point-in-time lighting, Daysim (which uses Radiance) for lighting over time, EnergyPlus for heat, electrical and fuel resource modelling, and OpenStudio for integration of Radiance and EnergyPlus (Rhino, n.d.). These tools are also more validated than the other two previous programs, making them more applicable to complex buildings that need a variety of analyses with dynamic facades. Table 1 summarises all of these analyses.

Table 1. A comparison of three software tools for simulating daylight

	Input Quality From the 3D Model				Model's Accuracy and Daylight Analysis			
	2D Model Visualisation	3D Model Visualisation	Daylight Analysis Visualisation	Imported Data From Other Modelling Software	Weather Data (EPW)	Daylight Validation	Detail Wall and Window Materials	Fast; Easy to Use
Dynamic Daylighting	✓	✓✓✓	✓✓✓	✓	✓	✓	✓	✓✓✓
VELUX Daylight Visualizer	✓	✓✓✓	✓✓	✓	✓	✓✓✓	✓✓	✓✓
Rhino Grasshopper	✓✓	✓✓✓	✓✓✓	✓	✓✓✓	✓✓✓	✓✓✓	✓

Conclusion

Based on the inquiry above, it demonstrates the potential of simulation tools in visualising daylight, providing a basis for designing optimum openings of buildings. The current development of software allows architects or designers to simulate the possibility of determining the size and placement of openings so that daylight can be present and improve the interior condition of the dwelling. If previously designing openings puts an emphasis based on the compositional aspect, visualisation of daylighting can be a crucial consideration from the early stages of designing buildings. The comprehensive information provided by the simulation tools become available for the architects or designers, so that the opening design becomes optimum in providing natural lighting with diffused or reflected quality, without having to gain heat.

Even though there are many lighting simulation programs available, an architect or designer can choose the best strategy to maximise daylight with an easy-to-use, fast, and realistic lighting simulation program. Simulations that are based on climate data, which includes real climatic data, allow a more realistic assessment of daylight performance to be made. Three simulation tools were analysed in this study that could be applied in tropical climates (Indonesia), such as Dynamic Daylighting, VELUX Daylight Visualizer, and Rhinoceros Grasshopper. Through the comparison based on the input quality from the 3D model and the accuracy of the model and daylight analysis, it is shown that in early architectural design stages, Dynamic Daylighting works best with simple rectangular shapes and windows, although this program requires a level of accuracy and detail that is usually reserved for lighting experts. VELUX Daylight Visualizer is more suited to residential design. It is not suitable to use in early architectural design stages. Once fundamental issues such as massing, building position, window size, and orientation have been addressed, the VELUX Daylight Visualizer can be used, showing that this tool is easy to use. As a last simulation tool, Rhinoceros Grasshopper can be used during early design stages and optimise the performance of the building. Designers can compare interactively the outcome of their intentions in the early design stages of design with more dynamic design since the program includes detailed weather data and environmental analysis.

This study shows that the simulation tools become useful for providing a basis when designing since different problems can be solved simultaneously. Despite that a more detailed and accurate tool performance evaluation with complete validation is needed, the accuracy of the model generated by the simulations and user-friendly interface would greatly assist in increasing the use of performance-based evaluations in the design. This study offers a better understanding of the three different simulation tools, particularly for architects, engineers, and students. Research in the future could explore simulations with different metrics and model complexity. This study demonstrates how visualisation through simulation tools provides the best reality through the visual images with more precise and quantifiable output quality, allowing the parameters to be involved that are crucial for designing in a tropical context.

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