VALIDATING GAME ENGINES AS A QUANTITATIVE DAYLIGHTING SIMULATION TOOL

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Abstract. This study aims to investigate the accuracy of representing daylit spaces using game engine-based rendering techniques, compared to validated benchmark renderers and real-life measurements. Two daylit case studies- reflecting different complexity levels and spatiotemporal settings- were rendered in a game engine using a traditional rendering technique and real-time raytracing. Illuminance levels at selected points were measured in Unreal Engine and were compared to those calculated in a validated light simulation tool and an illuminance meter for the simplified and complicated case studies, respectively. In both cases, traditional technique cited a high variance in illuminance levels compared to the references. In the simplified model, real-time ray tracing showed the lowest average error compared to the validated simulation results. In the complicated model, the average error of such technique was close to that of the validated simulation, compared to the actual illuminance measurements. This study illustrates the added benefits of using real-time ray tracing in game engines over traditional ray tracers to offer an immersive and interactive experience of virtual daylit spaces, without sacrificing the quantitative accuracy of the simulated luminous environments.

Keywords. Daylight simulation; game engine; ray tracing; immersive virtual environments.

1. Introduction

As the post-pandemic reality has substantially boosted the fact that people spent around 90% of their time indoors (Schweizer et al. 2007), it became a necessity to revisit the suitability of indoor environments to occupants' satisfaction. Daylighting design can play an immense role in defining a wide variety of buildings' performance qualities. On one hand, reliable daylighting strategies can partially mitigate the need for artificial lighting, and thus can considerably decrease building's annual energy consumption (Chi, Moreno, and Navarro 2018). On the other hand, daylighting availability has shown definitive positive effects on building occupants' wellbeing (Boubekri et al. 2014). However, excessive

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daylighting can cause visual and thermal discomfort (Nabil and Mardaljevic 2006), which may motivate occupants to rely on artificial lighting systems instead. Therefore, achieving a daylight strategy that considers quantitative and subjective preferences requires utilizing simulation tools at an early stage of design.

Due to its dynamic nature, the evaluation of daylighting in virtual settings requires high levels of accuracy in calculating the luminous environment. Physically-based light simulation tools, namely Radiance (Ward 1994), have been widely used as a benchmark in daylighting research, as they generate validated results against real-life scenarios and integrate spatiotemporal sky data. However, those tools require a time-consuming process to render a single lighting scenario, and often lack a user-friendly interface to interactively explore the simulated environment (Jones and Reinhart 2019). On the other hand, game engines can render highly realistic daylit environments in real-time where users can freely explore, evaluate, and customize different daylighting scenarios. However, the lack of validation studies on the luminous accuracy of game engine renderings can act as a barrier against a wider adoption of their advantages in daylight simulation studies.

This paper aims to investigate the luminous accuracy of game engine renderings against validated renderers as well as actual sensor measurements. Illuminance values of two case studies with different spatiotemporal and sky settings were compared across Radiance and Unreal Engine 4 with different render settings. The findings of this study push towards a wider validation of game engines as a simulation tool to represent accurate luminous qualities of daylit environments in a more immersive and interactive virtual setting.

2. Literature Review

Game engines can be defined as a set of tools for rendering, scripting, simulating Physics, and embedding artificial intelligence systems intended to create video games (Anderson et al. 2008). Game engines are based on real-time rendering to allow seamless communication between players and the game environment. Therefore, game engines use several techniques to optimize an adequate representation of lighting environments without sacrificing performance. One of those techniques is “baking” light maps, where light rays are traced, and the resultant effects of light and shade are projected over surfaces as textures (Geig 2013). While this technique can generate visually appealing results, it is limited when the light source is movable in real-time. In recent years, advancements in graphics hardware have enabled more accurate techniques to simulate lighting in game engines, mainly Real-Time Ray Tracing (RT), where physically correct renderings can be computed dynamically for a variety of global lighting effects, including reflections, refractions, and shadows (Gersthofer 2020). As RT basically simulates the behavior of light rays bouncing from the light source to different surfaces, a higher number of calculated bounces can improve the quality of the final output but can heavily affect system performance.

In daylight perception, game engines are often coupled with Virtual Reality (VR) hardware to offer an enhanced feeling of immersion and interactivity, which are two essential principles needed for a convincing virtual experience (Alshaer, Regenbrecht, and O'Hare 2017). In one study to measure perceptual impressions of daylit spaces in VR (Chamilothori et al. 2019), physically-based renders of an office space were projected in Unity 3D Game Engine as a textured cube map. In another study, a hybrid system that synergizes features of game engines with a validated raytracer was developed (Subramaniam et al. 2020). The developed tool offered an immersive virtual medium to assess visual comfort of indoor spaces. In a third study, an immersive light visualization tool was developed by integrating light simulation data from DIALux software with the Unity Engine (Wong et al. 2019).

In the discussed studies, game engines were only used as a supplementary tool to the physically-based images produced in validated renderers. While this shows the importance of accurate luminous effects daylighting in VR, it also highlights the limitations this approach brings to user experience. For example, using static images rather than walkable 3D meshes, limiting locomotion to head movement or teleport, and predefining the evaluated lighting scenarios. In this context, the limitations of Radiance software have been addressed by Jones and Reinhart (Jones and Reinhart 2019). Similarly, a few studies have employed game engines to improve the interactivity and immersiveness of user experience. Recently, Hegazy et al. (Hegazy, Yasufuku, and Abe 2020) employed Unreal Engine 4 (UE4) to develop an interactive system to visualize and assess daylit environments, where users can freely explore the environment in VR, change temporal settings, and report their perception of brightness using snapshotting tools. In a further application to a large-scale environment, daylight perceptions in the developed system were compared to those in the real environment, where consistency could be found between perceived brightness across reality and VR (Hegazy, Ichiriyama, et al. 2020). However, as daylighting performance metrics are often based on accurate calculation of illuminance levels, it is essential to conduct further validation to the accuracy of different game engine simulation techniques to adopt them in daylighting research and make use of their advantages.

3. Methodology

A wide variety of game engines have been used to simulate architectural and urban environments. However, the investigated game engine in this study was UE4 version 25.3, which was selected due to two reasons: 1) being the most widely used engine in architectural visualization (Jeff Mottle 2020) 2) possessing an advanced integration to real-time RT in terms of global illumination. Three rendering techniques in UE4 were examined for two case studies. The first technique is the traditional baked light map, in which the engine calculates lighting in non-real-time and projects the effects of light and shade on static surfaces. The second and third techniques were represented in real-time ray tracing with the number of bounces calculated varied between 3 and 7, to reflect different scenarios of balancing accuracy against performance.

3.1. SIMPLIFIED SHOEBOX MODEL

In daylight simulation, numerous parameters can affect the accuracy of the final results. This includes the surface properties, model complexity, and daylight portals. A simplified shoebox model was selected as an initial case study to eliminate the interference of these parameters and to focus on the accuracy of game engine rendering in a basic scenario. The simplified model is a 6x7x4 meters box with one rectangular opening (3x2 meters) oriented towards the South, with no glass window or furniture. As the selected model was generic, illuminance measurements in Radiance were adopted as the reference values compared to the outputs in UE4.

The model was created in Rhino 3D, lighting analysis was conducted on the model using DIVA for Rhino tool, which includes a fully-featured version of Radiance for physically accurate renderings. The spatial settings of the model were set based on the weather file for Osaka (JPN_OS_Osaka.Intl.AP) with a CIE clear sky. Temporal settings were set to September 21st at 9:00 am. One generic material (GenericInteriorWall_50) was applied on all surfaces of the model. As measurements were based on horizontal illuminance, an analysis grid of 0.6 meter spacing and 0.8-meter height above the floor was created using DIVA, generating 110 analysis nodes. However, to avoid redundant measurements, data included in the comparison was limited to 24 distinctive, uniformly distributed nodes (Figure 1 left). In UE4, the model was imported in FBX format. A spatiotemporal scenario for daylighting was realized using the SunSky system equipped with the Engine, which can be considered the equivalent of weather files in Radiance. This system can automatically adjust sun brightness and position, and sky conditions based on real spatiotemporal settings. In that aspect, geographical coordinates were set to 135 and 34 (Osaka, Japan), with identical temporal settings as in Radiance. Furthermore, a physically-based material matching diffuse color and reflectivity of Radiance material was created in UE4 and applied to the model. In UE4, materials are defined based on the physical properties of Base color, Specularity, Roughness, and Refraction. In this context, the generic Radiance material was translated to UE4 as (Base color=R 0.93 G 0.92 B 0.86, Specularity=0, Roughness=0.53). Illuminance levels at selected nodes were measured in UE4 using the HDR Histogram tool, which is integrated to the engine and can show absolute illuminance and luminance levels at any given point on the viewport, in a similar manner to the "Falsecolor viewer" tool in Radiance (Figure 1 middle and right).

In UE4, the output illuminance at selected nodes was measured under three rendering scenarios. In the case of the traditional baked lightmap technique, indirect lighting multiplier was set to 2, the reflection type was "screen space", and the simulation quality was set to "Highest". In the second and third scenarios, real-time ray tracing (RT) was used to calculate Global Illumination (GI), ambient lighting, reflections, and refractions. For GI, RT was set to "Brute Force", which is more GPU intensive but generates more accurate results. In RT, the number of bounces calculated can lead to a more realistic rendering while sacrificing performance. However, it can also affect illuminance levels measured due to more lighting being reflected to different surfaces. Therefore, a variation of 3 and 7 bounces was investigated as separate scenarios. (Figure 2) shows a rendering of the simplified model at the selected spatiotemporal settings, in Radiance and the three UE4 scenarios.

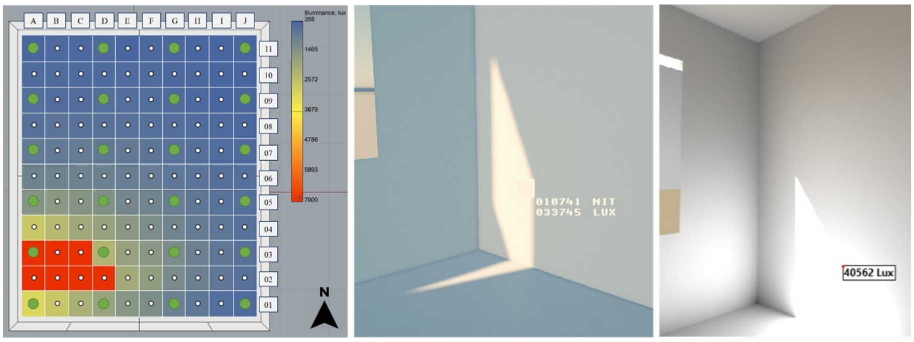

Figure 1. (Left) Measurement grid for horizontal illuminance generated in DIVA, nodes in green are included in the comparison. (Middle) measuring illuminance levels in UE4 using the integrated lighting analysis tool (HDR Histogram). (Right) Measuring illuminance at a given point for a Radiance output HDR image.

Figure 2. A point-in-time rendering for the simplified model; (a) Radiance, (b) UE4 with no RT, (c) UE4 RT 3 bounces, (d) UE4 RT 7 bounces.

3.2. COMPLICATED OFFICE MODEL

When it comes to daylighting simulation, one of the major advancements of game engines over traditional ray tracers is their ability to offer rich interactivity and immersion capabilities to the virtual environments explored. This can be represented in first person walkthroughs in real-time, collision physics, and dynamic sky system (full day cycle). However, these potentials cannot be highly illustrated in simplified models like the previously discussed case study, because they are too small to explore and have no objects to interact with. Therefore, game engines can show more potential for simulating daylighting in large, explorable spaces. Hence, the selection of the second case study was prone to the following criteria: first, to include a large-scale space. Second, both direct and indirect daylight effects should be available throughout the day. Third, to host a variety of related functions (i.e. meeting, studying, dining, computer-based work). Fourth, to be accessible by the authors for a prolonged period with the ability to control lighting conditions. An office building within a university campus was selected as it fulfilled the stated criteria (Figure 3 left). The test environment was limited to a common hall area on the 1st floor, which is daylit by a courtyard of 7.0m x7.0m dimensions. The investigated space hosts various study areas, meeting rooms with glass walls, a kitchenette corner, and an open conference hall (Figure 3 middle).

In this case study, illuminance levels measured in the real environment were taken as a reference to compare to Radiance and UE4. A set of 11 analysis points were selected within the central area of the space, reflecting a variety of directly and indirectly daylit, horizontal and vertical surfaces (Figure 3 right). Illuminance levels at these points were collected on March 18th, using a Konica Minolta T-10A luxmeter at 11:00 am (clear sky) and 2:00 pm (overcast sky), where all artificial lights were switched off and blinds were fully opened to ensure the space is only daylit. A digital twin of the test environment was modelled in 3DS Max software using the original floor plan drawings of the building as well as reference images of the current situation. Furthermore, surface textures (e.g. carpets, furniture) in reality were scanned and overlaid over respective surfaces in the 3D model. For lighting analysis in Radiance, the model was imported to Rhino 3D in FBX format. Due to the limitations of Radiance with complex scenes, polygon count of furniture was optimized, and surface textures were abstracted to average diffuse colors and applied as Radiance materials, with the consideration of the physical properties of different materials. In DIVA, the same weather file was used for the simplified model, and the 11 measurement points were created as analysis nodes in the same locations as reality. Simulations were run twice to reflect the two temporal and sky condition settings. On the other hand, the model was imported from 3DS Max to UE4 using Datasmith plugin, which ensures seamless conversion of meshes and textures between the two tools. In UE4, Base color was replaced by the scanned texture map of each surface, with accurate scaling. Other properties, such as specularity and glass transmittance were provided by the building's architect. As UE4 can handle large polygon counts, the original fully detailed objects were maintained without optimization. Lighting analysis and illuminance measurements in UE4 followed the same methodology and render settings discussed in (Section 3.1), generating three sets of scenarios reflecting different rendering techniques in UE4 (Figure 4).

Figure 3. (left) the lounge area in the selected case study. (middle) different functional areas within the selected case study, the measurement points included in the study are in areas C and D, J represents the courtyard. (Right) Sensor points selected for comparison, points H, I, J, and K are on vertical surfaces.

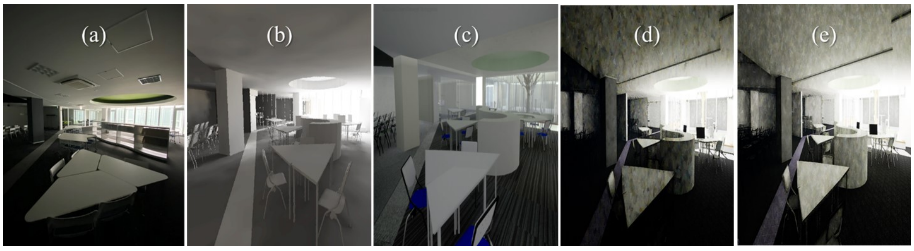

Figure 4. A point-in-time view at 11:00 am for the test environment, and its corresponding simulation outputs in different techniques. (a) real space, (b) Radiance, (c) UE4 with no RT, (d) UE4 RT 3 bounces, (e) UE4 RT 7 bounces.

4. Results and Discussion

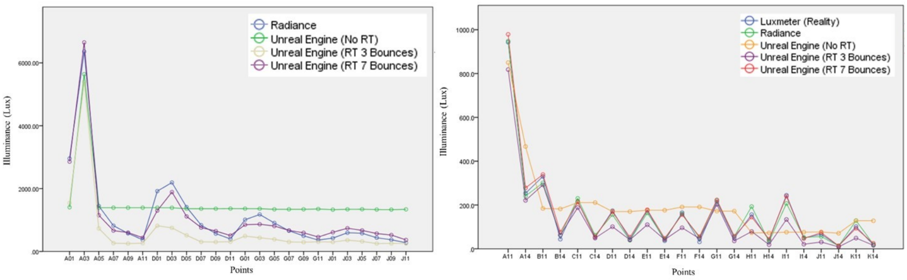

Figure 5. (left) illuminance measurements in the simplified model using different rendering tools. (Right) luxmeter measurements for the real office space, and respective illuminance measurements of its virtual replica in different rendering tools, point number reflect the time during which was measured (e.g., A14 is Point A at 2:00 pm).

In both case studies, the rendered images in UE4 showed its ability to generate results that are visually close to those produced in Radiance. Unlike Radiance, which needed about 2 minutes on a high-end workstation to produce one image, UE4 could generate the images in real-time allowing more freedom to explore virtually infinite views and lighting scenarios. However, this freedom imposes challenges in UE4 to balance between quality and performance. In other words, using RT with 3 bounce count led to highly noticeable artifacts (noise) within the produced scene, but it could be navigated smoothly at 60 frames per second (FPS). While rising bounces to 7 partially eliminated noise and increased the overall quality of the scene, it noticeably decreased the performance down to 24 FPS. This finding was more obvious in the complicated model, specifically in areas far from direct sunlight.

For the simplified model, illuminance levels at the selected points were compared between Radiance as a reference, and the three UE4 rendering scenarios (Figure 5 left). In all the four scenarios, illuminance values ranged between 200 and 7000 lux, with most measurements below the 2000 lux threshold. Through observational analysis, it was found that outputs of UE4 with baked lightmap technique (no RT) were the most varied from those in Radiance. Moreover, it was shown that this technique failed to distinguish between illuminance levels below 2000 lux, where redundant measurements of (1200-1300 lux) were found for most points with indirect daylighting. In contrast, outputs of RT renderings followed a similar pattern of values to that of Radiance. In the case of RT with 3 bounces, measurements were found to be consistently underestimated across all points, compared to Radiance. Increasing the bounces to 7 noticeably improved the results, specifically for points close to direct sunlight, while slightly overestimating the illuminance of the farther points (e.g., points J01-J11). In the complicated model, all illuminance levels were found to be below 1000 lux. Thanks to the availability of real-life measurements in this case, it was possible to compare the accuracy of UE4 renderings compared to a validated simulation tool like Radiance, taking luxmeter data as reference for both (Figure 5 right). As expected, Radiance results were very close to those of reality. As for the simplified model, renderings in UE4 no RT obviously varied from reality, with redundant values across points B-H in the two-day times tested. In the case of RT with 3 bounces, measurements showed a fewer variation from reality and followed the same pattern of high and low values. Moreover, RT with 7 bounces performed noticeably better, with a few values closer to reality than Radiance (points I11 and K11). Furthermore, the discrepancies between illuminance outputs of reference benchmarks and UE4 were quantified by calculating the relative error of each measurement compared to the reference, as well as the average error for all points (Table 1) using the following formula:

$$\frac{|InvestigatedValue - ReferenceValue|}{ReferenceValue} \times 100 \tag{1}$$

In the simplified model, the lowest and the highest errors in UE4 baked lightmap calculations were 3.7 and 381%, thus a very high average error of 126% was found for all points measured. This illustrated that on average, this rendering technique estimated illuminance levels as low as half or as high as double of the reference values. notably lower error ranges were found in the case of RT with 3 bounces, ranging between 8 and 67% and an average error of 44% for all points. In line with the observations, RT with 7 bounces showed the lowest average error (19.8%), with the lowest error of 1.5 and the highest of 40%. It is worth noticing that the deduced errors were referenced to Radiance and thus they reflect how close the measurements are to Radiance calculations rather than absolute values in real life. In the complicated model, error percentages were referenced to the luxmeter data. As expected, Radiance showed the lowest average error (15%) across all points, with the lowest and the highest errors as 0.5 and 60% respectively. UE4 baked light map showed an average error even higher than that in the simplified model (162%), illustrating a high discrepancy in estimating illuminance levels in the complicated, textured environment. However, RT with 3 bounces showed better results, with an average error of 30%, 5%, and 56% as the lowest and the highest errors respectively. Furthermore, results of RT with 7 bounces showed almost similar average error (15.8%) as that in Radiance. Following the recommendations by Fisher (Fisher 1992), an acceptable error range between measurements and simulation should be 10% for average illuminance calculations and 20% for each measurement point. While the average error for UE4 RT renderings slightly exceeded this threshold, it is also worth noticing that it was the case for Radiance, meaning that in this specific study, UE4 RT could quantitatively output results that match the accuracy of a validated ray tracer. Moreover, as discussed by Reinhart and Anderson (Reinhart and Andersen 2006), it is worth noticing that the ultimate sensor that perceive and assess the appearance and brightness of daylit spaces is the human eye, and thus the difference between 400 lux and 500 lux (20% error) might not be humanly noticeable in the first place. As shown in Figure 3 and Figure 5, UE4 could generate images that are more visually similar to Radiance in the case of the simplified model. On the contrary, the quantitative accuracy of the measured points was higher in the case of the complicated model. The reasons for this drop in accuracy for the simplified model renderings despite the lack of interfering parameters are not clear, thus it is important to investigate such aspects on a wider range of cases and spatiotemporal settings.

Table 1. Average relative errors for all the measured points compared to references.

Case	Reference	Number of points	Average error of all points (%)			
			Radiance	UE4 No RT	UE4 RT3	UE4 RT7
Shoebox	Radiance	24	-	126.1	44.2	19.8
Office	Reality	22	15.0	162.7	30.6	15.8

5. Conclusions

This study investigated the luminous accuracy of Unreal Engine based on point-in-time illuminance values. Two daylit case studies were selected to reflect different spatial complexity levels, and three rendering techniques were used to generate the scenes. For the simplified case study, ray tracing with 7 bounces showed the least varied results from Radiance, while renders from baked lightmap performed the worst. In the complicated case studies, results from Radiance and Unreal Engine were compared to luxmeter data in reality. Likewise, raytracing with 7 bounces showed an average error that is very close to that in Radiance. To the authors' knowledge, this study is one of the very first to address the adequacy of game engine-based renderings in daylighting research, specifically in application to real-time ray tracing techniques. While the findings of this study are not conclusive, they clearly illustrate the potential of the newly introduced techniques in calculating illuminance levels with an accuracy that is comparable to benchmark tools, with the added benefits of instant feedback and interaction. With the advancement of hardware, real-time ray tracing is witnessing rapid development, and more game engines are implementing their own ray tracing techniques (e.g., CryEngine and Unity). A future direction of this study is to compare the accuracy of other game engines against Unreal. As the interactivity and immersion offered by game engines pose a useful application in human perception studies of daylit spaces, the authors would conduct a further study to investigate the accuracy of game engines in luminance measurements, as they closely relate to what the human eye perceives. Also, more complicated daylighting scenarios (e.g. reflectors, Venetian blinds) and climate regions would be included in future case studies.

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