Evaluating Daylighting Analysis of Complex Parametric Façades

Mohamed Gomaa[1], Wassim Jabi[2]
[1]Tanta University [2]Cardiff University
[1]msrgomaa@gmail.com [2]jabiw@cardiff.ac.uk

Lighting analysis tools have proven their ability in helping designers provide functional lighting, increase comfort levels and reduce energy consumption in buildings. Consequently, the number of lighting analysis software is increasing and all are competing to provide credible and rigorous analysis. The rapid adoption of parametric design in architecture, however, has resulted in complex forms that make the evaluation of the accuracy of digital analysis more challenging. This study aims to evaluate and compare the performance of daylighting analysis in two industry standard software (Autodesk Revit and 3ds Max) when analysing the daylighting of complex parametric façade patterns. The study has shown that, generally, both Revit and 3ds Max underestimate illuminance values when compared to physical scaled models. 3ds Max was found to outperform Revit when simulating complex parametric patterns, while Revit was found to outperform 3ds Max when simulating simple fenestration geometries. As a general conclusion, the rapid progress of parametric modelling, integrated with fabrication technologies, has made daylighting analysis of complex geometries more challenging. There is a need for more sophisticated algorithms that can handle the increased level of complexity as well as further verification studies to evaluate the accuracy claims made by software vendors.

Keywords: *Daylighting analysis evaluation, Parametric patterns, Revit, 3ds Max, Complex façades*

INTRODUCTION

The use of lighting analysis tools is becoming increasingly important. These pieces of software have proven their ability in helping designers provide functional lighting, increase comfort levels in spaces and reduce energy consumption through the use of natural light (Maamari et al. 2006). Consequently, the number of lighting analysis software is increasing around the world and all are competing to provide credible and rigorous analysis results, while, ironically perhaps, the error margins of the results are still high. Thus, identifying the lighting software's capabilities and limitations as well as validation studies play an important role.

Over the last two decades, several associations have been conducting studies in the field of lighting software validation (e.g. CIE Technical Committee, BRE-IDMP and NRC) (Tsountani & Jabi 2014).

These associations have produced a number of technical reports and test cases that have set clear guidelines for evaluating the accuracy of lighting analysis tools (Maamari et al. 2006; Tsountani & Jabi 2014). The rapid adoption of parametric design in architecture, however, has made the evaluation of the lighting software's accuracy more challenging. The complex shapes and geometries produced by many modelling software have made evaluation using simple technical reports inapplicable and unreliable.

HYPOTHESIS, AIMS AND OBJECTIVES

Digital design software for architecture seeks to increase the efficiency of design process by integrating performance analysis tool with parametric modelling. While the lighting analysis engines in Revit and 3ds Max have been validated against other industry-standard engines such as Radiance and against physical scale models, there are no published studies to date that test their capabilities when used to simulate daylighting in complex façade geometries. 3ds Max Design has been well validated and has been proven to be highly reliable for performing daylighting analysis as concluded by a number of authors such as Reinhart & Breton (2009) and Tsountani & Jabi (2014). Yet, there are still some concerns regarding its accuracy in lighting analysis for complex geometries (Tsountani & Jabi 2014). Several authors such as Carroll (1999), Bazjanac & Kiviniemi (2007) and Tsountani & Jabi (2014) have been emphasizing the importance of integrating performance analysis with advanced parametric modelling in the early design stage.

This study aims to assess the capabilities and accuracy of the daylighting analysis for complex parametric façade geometries using two popular pieces of software (Autodesk Revit and Autodesk 3ds Max). Both products combine parametric design tools with daylighting analysis tools and both claim to have the ability to generate accurate analysis for complex geometries, which can be produced by the parametric tools. The key difference between them is that Revit is designed mainly for building information modelling (BIM), while 3ds Max is more suitable for parametric 3D modelling, visualization and animation.

METHODOLOGY

The methodological approach of the study is experimental, based on four main test cases. Each test case consists of a comparison among three types of models; Revit 2015, 3ds Max 2015 and a physical scaled model. The limited time and resources have prevented performing comparisons with actual built cases. However, physical scaled models are considered a reliable validation method for the illuminance prediction in real spaces by many lighting researchers (Love & Navvab 1991; Mardaljevic 2001; Thanachareonkit et al. 2005). As a consequence, it has been also considered as a trusted technique for producing benchmarks for validating lighting software (Mardaljevic 2001). In this study, the scaled model is used as a baseline case for comparison purposes. While it is understood that the accuracy of physical scaled models varies in relation to the 1:1 construction, they serve as a stand in and their inaccuracy is taken into account in the reported results. It is planned to use actual built cases in future studies.

These test cases form a set of four different modelling and simulation challenges. Each test is conducted in two different overcast sky conditions; midsummer and mid-winter. The chosen location is London, United Kingdom. The tests use a simple rectangular room with unglazed opening at the southern façade. This opening is where the different patterns in each test are placed. The initial test (test 1) simulates the room with simple unglazed opening. The next set of tests (2, 3 and 4) use three types of parametric patterns to form the façade geometries, which approximate some of the commonly used techniques in modern building envelopes. These techniques are force-field, packing, and weaving respectively.

The room model and the parametric patterns for each test were built then daylighting analysis was performed using the available tools in each software. The assessment of results depends mainly on evalu-

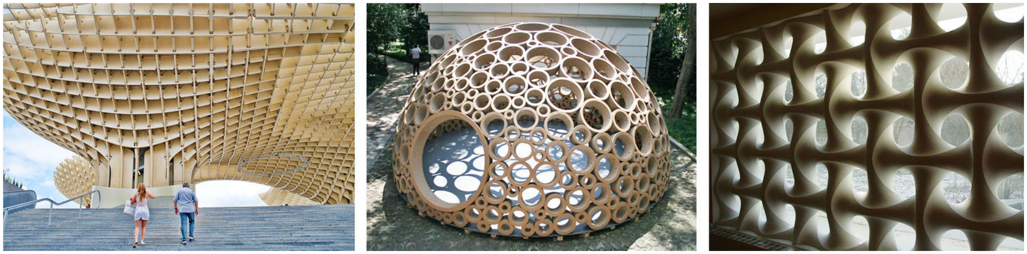

Figure 1
The figure shows examples of the three chosen patterns; the force field in Metropol Parasol Seville in Spain, the packing in packed pavilion in Shanghai and the weaving pattern geometry by Erwin Hauer [1; 3; 4].

ating the discrepancies in illuminance values as reported by Revit and 3ds Max and by comparing those to measurement of illuminance values in the physical scaled model. The physical scaled models were produced by 3d printing and laser cutting processes. In order to assure the accuracy of the comparisons, identical boundary conditions and material properties were maintained among all models.

METHODOLOGY OF CHOOSING THE PARAMETRIC PATTERNS

These patterns represent three different algorithmic thinking techniques. They were chosen based on the findings from two books; *Elements of Parametric Design* by Woodbury (2010) and *Parametric Design for Architecture* by Jabi (2013). These patterns represent the main possible challenges when using parametric design for producing façades' patterns or building's envelope structure.

The force-field technique was chosen to represent the use of complex shading devices, which formed as a grid of vertical and horizontal louvers. These louvers have changing depths to simulate different needs of indoor daylighting conditions. The packing technique offers an economic and efficient way of using materials and spaces while combining other parametric concepts such as tiling and subdivision (Jabi 2013). The main challenge of using packing in daylighting simulation is in calculating the light penetration through perforated screens. Finally, the weaving technique represents a high level of complexity. Formations by weaving contain a large number of curves while the interlacing of threads creates complex double-skinned geometries. These factors are considered as a highly challenging test for the ability of any software to perform daylighting analysis accurately. Figure 1 shows examples of using these three patterns in real projects.

MODELLING DETAILS OF TEST CASES

Test 1 was conducted using the room without adding patterns to the southern façade. This test was considered as a baseline case to obtain a basic overview of the calculations' accuracy within the virtual models as compared to the scale model measurements. The second test used the force-field technique to produce the façade pattern to fill the opening at the southern façade of the room. It was designed with variable depths ranging from 15.0 to 60.0 cm in order to simulate the most commonly used depths for shading and louvers. The grid size of pattern was set to (30.0*30.0) cm. The third test used the packing technique. The pattern contained multiple numbers of circles which have variable diameters ranging between 5.0 and 50.0 cm. The thickness of the pattern was set to 15.0 cm. The final test used the weaving technique. The dimensions of a real sculpture by Hauer (2004) were used in this study. The pattern contained two main interlacing layers. The thickness of each layer was set at 5.0 cm while the maximum gap distance between them was set at 10.0 cm. This resulted in an overall maximum thickness of 20.0 cm for the overall pattern. The design of the pattern produced a number of small openings with a maximum width and height of 40.0 cm and 20.0 cm respectively.

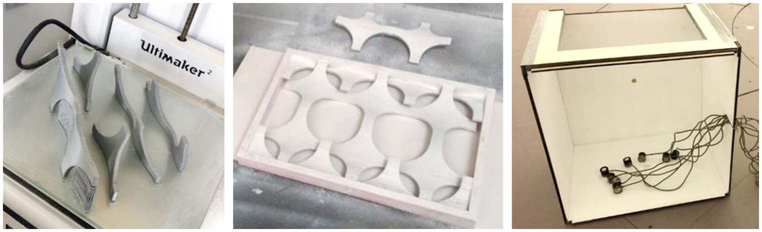

Figure 2
Photos show the process of producing the physical model geometry. Source: author

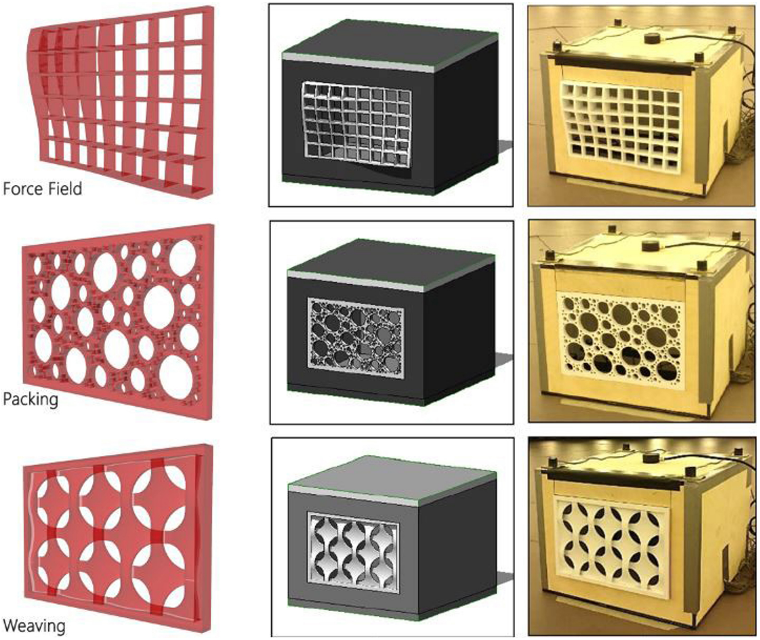

Figure 3
The virtual and physical models for test 2, 3 and 4 (Surrounding envelope removed in images of virtual model for clarity). Source: author

DEFINING MODEL SPECIFICATIONS AND FABRICATION PROCESS

Test cases were conducted using a simple rectangular room with dimensions of (4*4*3) m. This room was designed to be similar to the one used in other validation studies such as CIE 171:2006 technical report. This room has an unglazed opening on the southern façade with dimension of (3*2) m. The opening is filled with a different parametric pattern in each test. All inner surfaces were white painted with an average reflection ratio of 91.0 %. The scale model envelope was fabricated by a laser cutter machine using plywood sheets. Using other materials to produce the envelope would not affect the testing process as the most important factor is the final reflectivity of the surface material. The inner surfaces of the envelope were painted with 5 layers of white spray with 30 min time interval between each layer in order to achieve consistent and homogeneous reflectivity. The model scale is 1:10 in order to fit the overall scale of the testing area and to fit the photometric sensors as well.

Figure 4
Testing physical models at the artificial sky dome. Source: author

The parametric patterns were fabricated using PLA material by an Ultimaker 2.0 3d printer. The Ultimaker printing platform is limited to (20*20*18) cm. Thus, it was necessary to divide the patterns geometries into smaller parts to make them fit into the printing area. These parts were then assembled to form the final geometry before painting. Patterns were painted in white as well to produce high reflectivity. All three patterns had an average reflectivity ratio of 85.0 %. The white paint finish was chosen to achieve better light distribution inside the model (Tsountani & Jabi 2014) while it is also closer to the real finishing used in building interiors. Figure 2 shows the process of producing the physical model geometry, while Figure 3 shows the virtual and physical models for test 2, 3 and 4.

DEFINING BOUNDARY CONDITIONS FOR THE TEST CASES

The boundary conditions for the testing process were based on two periods throughout the year in order to assess different types of sky illuminations. The first period is a winter scenario measured on January 21st while the second period is a summer scenario measured on June 21st. The simulation time is 12:00 pm in order to gain the highest altitude of the sun. The sky condition for validation testing using a scale model is recommended to be an overcast sky (Mardaljevic 2001; Thanachareonkit et al. 2005). It is also recommended for artificial sky testing as there is a large discrepancy in illumination between a real sun and an artificial sun and also to avoid the penetration of direct sun rays into the model (Mardaljevic 1999). The test location was set to London, UK. The boundary condition of the scale model was produced by using an artificial sky dome (see Figure 4). The measured lux level from the artificial sky was used for sky illuminance input in both Revit and 3ds Max.

MONITORING AND EVALUATING TEST RESULTS

The test target is to monitor and record the illuminance values in Lux taken on a working plan with a height of 0.75 cm, based on the LEED accreditation requirements (au.autodesk.com 2016). Lux values are recorded using sixteen sensor points distributed on an orthogonal grid (1*1) m (see Figure 5). Another four sensors were used on the top (for the scale model) to measure the average of sky illumination level. These illuminance levels were used in the analysis setting of Revit and 3ds Max to ensure identical boundary conditions. The comparisons used values from each column of sensors separately, starting from column 1 and moving to column 4 while also moving from row A to row D. Two main items were assessed, the first was the consistency of software analysis to the physical scale model measurements (general trend of the charts) and the second was the percentage of discrepancy between the virtual and the physical scale model. 12 "Megatron Selenium" photo-electric cells connected with the "Agilent 34970A Data Acquisition" control logger were used to record the illuminance measurements. The reflection ratios from physical model parts were measured using the Luminance meter 'Minolta LS-100'.

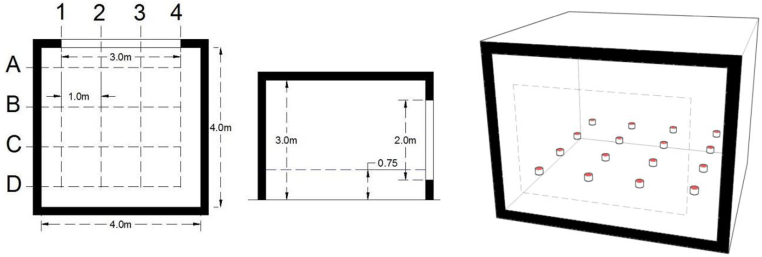

Figure 5
Room's plan, section and perspective including the sensors grid dimension and design. Source: author

PREDICTION OF ERRORS

Interpreting the results was based on assessing the amount of discrepancies. The eventual result will be evaluated after checking the available error bands. A number of researchers have outlined different causes of errors when using scale models in validation (Schiler 1987; Love & Navvab 1991; Thanachareonkit et al. 2005; Aghemo et al. 2008). These expected causes are as follow:

- Parasitic light penetration into scale models.
- Sensors levelling and placement in the scale models.
- Surfaces reflectance.
- Lux meter calibration.
- photocells size (sensing aperture).

Different literature sources, including the ones mentioned previously, were checked to gather the final error margins for this study. These sources have used different pieces of software besides using scale models or real buildings for validation. The next table (Table 1) shows the reported error bands by each literature source:

From Table 1, it is concluded that scale models mostly overestimate the results when compared to real tests. This over-estimation is agreed to be up to 50% and in extreme cases could reach 60%. However, the average reported error of 40% is used for this study. On the other hand, the reported error bands from comparing software to real cases or benchmarks vary between 10% to 25%. Since this study focuses on 3ds Max and Revit, the used error band is based on the recommendations from Reinhart & Breton (2009) and Tsountani & Jabi (2014) who studied 3ds Max and set the error band between 10% and 20% of under-estimation. Thus, an average of 15% under-estimation is used in this study. As a consequence, there is an overall predicted error band for this study of 55.0 % (40.0 % + 15.0 %). This is predicted as an underestimation of the lux levels in software analysis when compared to the physical scaled model.

For further detailed assessment, the discrepancies were categorized into two stages of error bands: the lower error band (20.0 %) and the higher error band (55.0 %). The lower error band was chosen to reflect a high accuracy analysis and to represent the maximum error by Reinhart & Breton's study (2009). The higher error band is the maximum limit for error. Discrepancies which exceed the 55.0% reflect a lack of accuracy by the software.

DISCUSSION

Based on the findings from the four tests, it is generally noticed that both Revit and 3ds Max are underestimating the illuminance values as compared to the physical scaled models. This under-estimation by software was expected as discussed previously. In test 1, where a simple opening model is used, Revit has shown an overall better performance than 3ds Max. However, the differences in discrepancies between Revit and 3ds Max were not high, as the majority of discrepancies in both pieces of software located within the lower error band (20 %) while no discrepancies exceeded the higher error band (55 %). In addition, the discrepancies in both Revit and 3ds Max were at their lowest values nearest to the open-

Table 1
Recorded error bands by different literature. Source: author

Literature	Type of study on Daylighting	Error band
Tsountani & Jabi (2014)	3ds max compared to CIE 171:2006 technical report	±10 to 20%
Schiler (1987)		
Love & Navvab (1991)		
Thanachareonkit et al. (2005)	Scale model compared to real case Building	+30 to 50%
Aghemo et al. (2008)		
Mardaljevic (2001)		
Mardaljevic (2001)	Radiance compared to real case building	± 10 to 25%
Galasiu & Atif (2002)	Adeline compared to real case building	+ 25%
Reinhart & Breton (2009)	3ds max and dialux compared to real case building	± 17 %

ing. Overall, test 1 has revealed that Revit is producing more accurate daylight analysis than 3ds Max for simple geometries.

Starting from test 2, as the daylight analysis conditions became more complex by adding the parametric patterns to the room opening; the performance of Revit drops when compared to test 1. Although both Revit and 3ds Max suffered a drop in daylighting analysis performance in test 2, 3ds Max has shown superiority over Revit. All discrepancies in 3ds Max located below the higher error band of 55 % in both scenarios, while in Revit they were 75.0 and 56.0 % in the same order. The superiority of 3ds Max remained in tests 3 and 4 as well. Yet, it is noticed that the daylight analysis performance by both Revit and 3ds Max decreased gradually when moving from test 1 to test 4. As shown in Figure 6 and 7, the discrepancies trend in all scenarios increased after applying more complex geometries. Test 4 results have the highest discrepancies in both software. The highest recorded discrepancy is 70.0 %, which is recorded in Revit and 3ds Max in test 4. This exceeds the higher error band by an extra 15.0%.

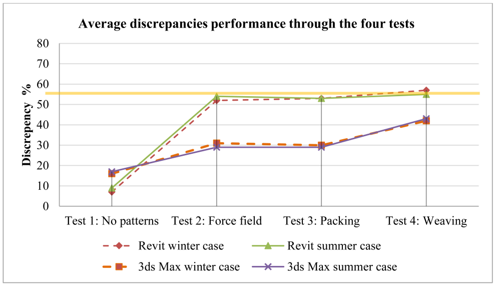

Figure 6
Graph of average discrepancies performance throughout the four main test cases

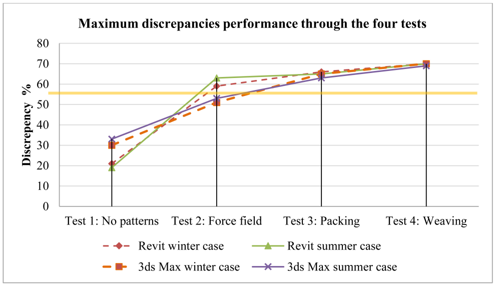

Figure 7
Graph of maximum discrepancies performance throughout the four main test cases

Test	Scenario	Software	Minimum discrepancy %	Maximum discrepancy %	Average discrepancy %	Points within lower Error band %	Points within higher Error band %	Points above higher error band %
Test 1: No patterns	Winter case	Revit	0.0	21.0	7.0	94.0	6	0
		3ds Max	3.0	30.0	16.0	67.0	33	0
	Summer case	Revit	1.0	19.0	9.0	100.0	0	0
		3ds Max	4.0	33.0	17.0	69.0	31	0
Test 2: Force field Pattern	Winter case	Revit	32.0	59.0	52.0	0.0	75	25
		3ds Max	12.0	51.0	31.0	19.0	81	0
	Summer case	Revit	43.0	63.0	54.0	0.0	56	44
		3ds Max	6.0	53.0	29.0	25.0	75	0
Test 3: Packing pattern	Winter case	Revit	33.0	66.0	53	0.0	57	43
		3ds Max	3.0	65.0	30	19.0	75	6
	Summer case	Revit	29.0	65.0	53.0	0.0	62	38
		3ds Max	2.0	63.0	29.0	19.0	75	6
Test 4: Weaving pattern	Winter case	Revit	45.0	70.0	57	0.0	50	50
		3ds Max	0.0	70.0	42	6.0	63	31
	Summer case	Revit	33.0	70.0	55.0	0.0	44	56
		3ds Max	14.0	69.0	43.0	19.0	56	25

Table 2
Different recorded discrepancies in Revit and 3ds Max in the four test cases.

To summarise, the average of discrepancies from Figure 6 show satisfactory results, as Revit exceeds the higher error band only in the winter case scenario in test 4, with a small difference of 2.0%. On the other hand, the maximum of discrepancies from Figure 7 shows that both Revit and 3ds Max exceed the higher error limit in tests 3 and 4. However, 3ds Max has shown that the majority of its discrepancies are located below the higher error band with percentage between 69 and up to 100 % of sensor points (see Table 2).

The last three columns in Table 2 show the percentage of points on the sensor grid that have discrepancies within and above error bands per each test case. For example, the first row of values in the table shows that in Revit winter case, 94.0% of points are located within the lower Error band. This means that 15 out of 16 sensor points have discrepancies values that are lower than 20.0%. The following graphs in Figure 8 outline the percentages of these points in each test case.

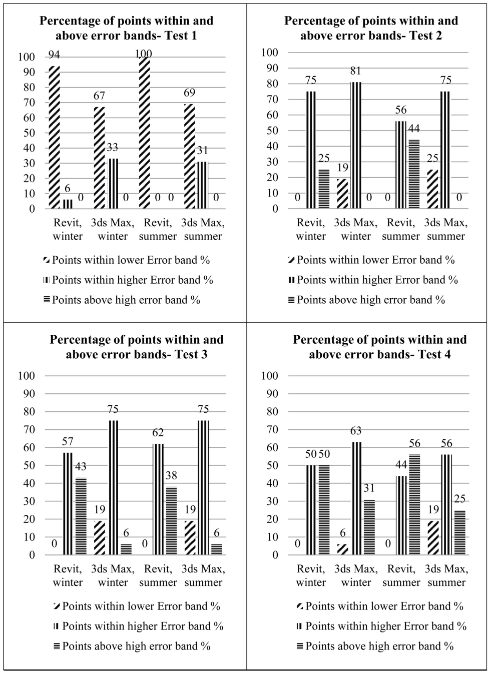

Figure 8
The percentage of points within and above error bands in each test case in both winter and summer scenarios.

CONCLUSION

The final conclusion regarding which software is performing better daylighting analysis depends on two main questions. The first question is *what level of complexity do the project's geometries have?*, while the second is question is *what level of accuracy is needed?*. This study has found that the claims of Autodesk about Revit's capabilities are correct only when simulating simple geometries such as the model in test 1. It is proven through test cases 2, 3 and 4 that Revit has low performance of daylighting analysis when simulating complex patterns. In contrast, 3ds Max has shown better performance when simulating complex patterns.

Based on these findings, Revit is recommended to provide a fast and credible daylighting analysis for simple forms and only in the early stages of design when high levels of accuracy are not required. Revit also can be useful to obtain an initial insight regarding the daylighting distribution inside the model even with the complex patterns. However, users should expect an overall under-estimation of illuminance values. If more sophisticated daylighting analysis is required, then 3ds Max is highly recommended for the task. As a general conclusion, the rapid progress of parametric modelling, integrated with fabrication technologies, has made daylighting analysis of complex geometries less credible. The existing daylighting simulation tools need validations and urgent upgrades in order to narrow the increasing gap between predictions and physical reality.

The followed methodology in this study has helped in achieving the required aims. The main obstacle for the study was the limitation in time and facilities. However, there are several suggested improvements which could raise the efficiency of the study's experimental part. These suggestions are as follow:

- To use real sky conditions instead of using the artificial sky in simulating the daylight system in the physical scale models. This can minimize the possible errors related to calibrations of the artificial sky illumination or the maintenance of hardware such as light bulbs, but will produce its own challenges.
- To calibrate test 1, as baseline verification, with an actual built situation as a starting point including comparative measurements to the physical model. This will increase the relevance and significance of this research.

Further studies are recommended on evaluating the daylighting analysis in Revit and 3ds Max using clear sky conditions. These further tests shall include glazing in the façades, whether transparent or translucent.

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