DAYLIGHT MAPPING USING KRIGING

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ABSTRACT

Kriging is a group of geo-statistical techniques used to interpolate the value of a random field at an unobserved location from discrete observed values at nearby locations. Kriging has been developed to interpolate climate data as a probabilistic method.

Kriging has been very popular in oceanic research used for predicting the variance of geographical conditions. However, it has been difficult to find a similar application in the built environment. This paper aims to uncover possibilities of using Kriging for built environment studies, specifically focusing on indoor light level.

Kriging interpolates with the discrete point data of light level to the continuous field. This may suggest a new approach to save computational expenses with reasonable accuracy in comparison to physics based computational simulation results.

INTRODUCTION

Kriging has been developed to interpolate climate data. This probabilistic method incorporates randomness and allows for the inclusion of the variance and statistical significance of the predicted values. In geoscience application, Kriging is the best interpolation technique available when data is sparse (Burrough and McDonnell 1998).

As the primary probabilistic method available, Kriging has been suggested for analyse of climate data. With the given low resolution data from GIS, higher resolution data could be generated by Kriging techniques (Sluiter 2009).

The Kriging process starts with the recognition of irregularities in spatial variations. A Regionalized variable substitutes the simple function to solve for the random behaviour. In general, Kriging is a relatively fast interpolator that can be exact or smoothed (Isaaks and Srivastava 1989).

The Kriging method can be applicable to building simulation, especially with analysis that requires a profile of the plot, such as light level, airflow, and temperature distribution. Kriging could statistically predict the continuous field of conditions with a select number of data points which saves on computational costs that is otherwise highly expensive in physics-based field prediction for the same area.

This paper aims to find possibilities of using Kriging for the building environment. Light level was selected as a test domain, specifically concerning indoor light level change according to sun movements and sky conditions in the daytime. Full physics-based simulations for natural light studies are typically conducted for selected occasions (the worst conditions of the year) or are used with a small number of selected measurement points to study indoor light levels for the whole year. The major hedge for light simulation is related to the computational power and time required to conduct a full year simulation in order to map out 2D or 3D indoor light level profiles.

Currently, EnergyPlus uses Daylight Factor (DF) (UIUC 2005) to capture the complexity of daylight behaviour. However, DF has difficulty addressing realistic light conditions because direct sunlight is not accounted for when making overcast sky assumptions. For an accurate prediction of natural light, it is important take into account illuminance, the total luminous flux incident on a surface per unit area.

However, the main obstacle with physics based simulation still lies with its computational expense, which led to the development of the Daylight Autonomy measurement (Reinhart, Mardaljevic et al. 2006). With daylight autonomy, only a few selected measuring points (locations) are required to understand the yearly behaviour of daylight. Increasing the number of points would generate the corresponding additional information, while essentially increasing the simulation time. Thus, efficiently integrating the light domain with thermal calculations remains a major hurdle for building energy simulation tools (Reinhart, Mardaljevic et al. 2006).

The paper proposes a prediction method using Kriging to interpolate the profile or distribution of illuminance from select data points. This proposed method will be able to produce light distribution, such as DF, but obtain more realistic results while reducing computational expense through statistical methods.

IMPLEMENTATION

Kriging has a few different models. In this paper, the ordinary kriging method was used. Other models may include algorithms called simple, universal, and indicator. More details of each indicators can be found in several existing papers (Armstrong 1984; Journel and Posa 1990; Olea 1991).

The basic technique used by the ordinary kriging method is a weighted average of neighbouring samples to estimate the 'unknown' value at a given location. Weights are optimized using the semi-variogram model, which indicates the location of the samples and all the relevant inter-relationships between known and unknown values. This technique also provides a "standard error" which may be used to quantify confidence levels. The paper defines the modelling process of kriging in four stages: 1) data preparation, 2) semi-variogram, 3) kriging, and 4) validation.

1. Data preparation: This stage provides the input data for kriging. Typically, the data consists of 2D or 3D Cartesian coordinate (x, y, z) point values and each point's relevant value.
2. Semi-variogram: The semi-variogram function quantifies the assumption that things nearby tend to be more similar than things that are farther apart. Semi-variogram measures the strength of statistical correlation as a function of distance.
3. Kriging: Based on the semi-variogram function measured, values are weighted to derive a predicted value for nearby surrounding unmeasured locations.
4. Validation: Measurement errors occur when several different observations are possible from the same location. Based on the error and the kriging-variance map, reliability of the prediction can be found.

Based on the above kriging modelling process, the paper proposes a method to predict illuminance map shown in Figure 1. The method consists of three major parts - preparation, daylight simulation and kriging interpolation. In the preparation stage, boundary conditions such as geometry, material properties, sky conditions and illuminance measurement points are determined. This information is then passed to an advanced daylight simulation tool to model and simulate indoor light conditions. Once the simulation is complete, illuminance values of selected points and their location coordinates are passed to the kriging stage. Next, the simulated location coordinates and illuminance values are used as input data values for kriging. These values are used to find the relative weighted value by the semi-variogram model. Once the optimized weights are found, the kriging process predicts the values of the surrounding unmeasured locations. Following the kriging process, the predicted values are verified to determine whether they are within the error range.

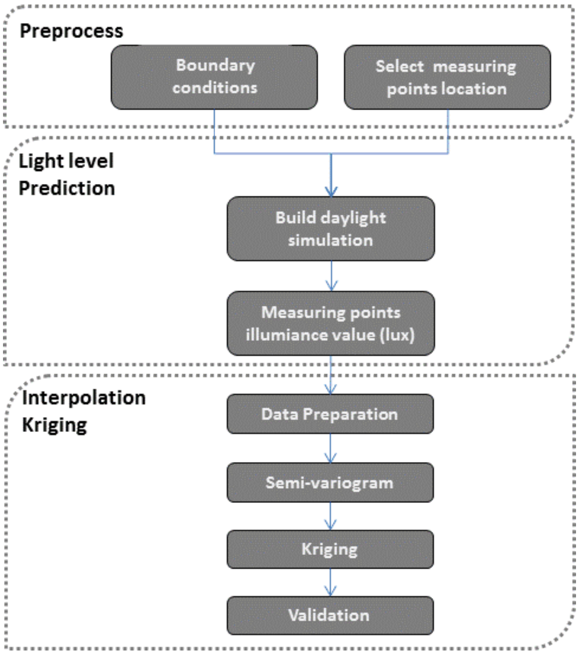

Figure 1 Kriging process for light level interpolation

The proposed method reduces the light simulation time by introducing the kriging prediction method. In order to determine the proposed method's accuracy and robustness, the paper evaluated its potential by testing a simple case.

EVALUATION

A test space is selected to compare the kriging results with typical light simulation results. Comparison between the proposed kriging method and a conventional simulation method shows that results produced by the proposed method comes close to those produced by the simulation result which provides an in-depth understanding of how much computing time can be saved.

The test location is Philadelphia, PA, US. The test space is located on the fourth floor of a building that

Table 1 Building information

Location		Philadelphia, PA, USA
Latitude, Longitude		39.9522 N, 74.1642 W
Interior dimension		5200 (D) x 3400 (W) x 2300 (H) (mm)
Interior wall	Color	White
	Reflectance	0.63
Window size		580 (W) X 2300 (H) (mm)
Glazing properties	Reflective	0.52
	Emissivity	0.78

faces south. The south façade of the selected test space has three windows of the same size. The size of the space is 3.4m wide, 5.2m deep, and 2.3m high. Interior surfaces are painted white on plaster with a reflectance of 0.63. Table 1 and Figure 2 provides additional details of the boundary and geometric conditions of the test case.

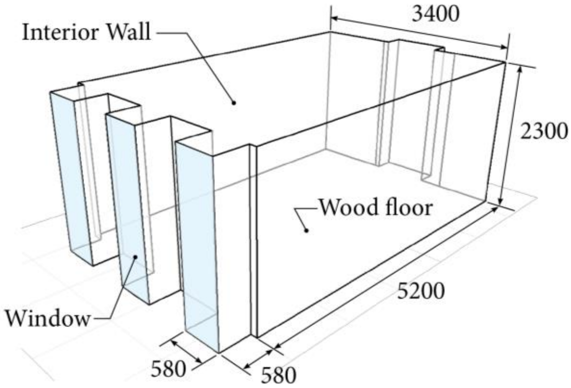

Figure 2 Building geometry (unit:mm)

The test space was simulated using two different cases - one with a selected number of points and another with 2,500 points (50 X 50 analysis grids with a size of 68mm X 104mm per grid). Illuminance results of the selected points case were passed to Kriging to predict the around test points' illuminance values. Once Kriging predicts the illuminance, these values were compared with the full illuminance simulation result. (Figure 3)

The test used Radiance as a light simulation tool (LBNL 2000) and EasyKrig3.0(Chu 2004). Radiance is highly accurate ray-tracing software for analysing and visualizing lighting in design. Luminance, illuminance and glare indices can be produced as color maps with three-dimensional geometry, materials, time, data and sky conditions (Ward 1994). Validation has been conducted to show the model's accuracy with real conditions (Mardaljevic, Lomas et al. 1993). EasyKrig3.0 is a Kriging software package utilizing the MATLAB Graphic User Interface (GUI). One of the main advantages of EasyKrig3.0 is that it automatically predicts the initial parameters that can be changed in subsequent processes.

Table 2 test scenario cases

Scenario	*Date*	*Time*	*Kriging input point numbers (grid size)*
1	June 21st	Noon	117 (9X13)
2	June 21st	Noon	35 (5X7)
3	June 21st	Noon	12 (3X4)
4	Dec 21st	Noon	117 (9X13)

The evaluation process conducted several scenarios, which are outlined in Table 2. All scenarios used the same sunny sky condition. The primary reason for this is to utilize full illuminance studies to consider direct sunlight impact on indoor illuminance levels

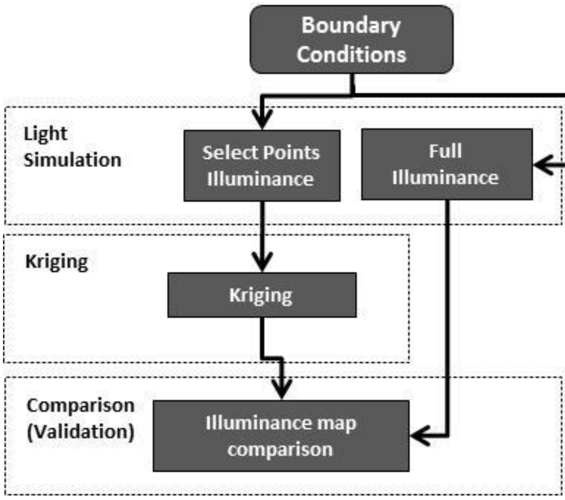

Figure 3 evaluation process

which is difficult to do with DF. Scenarios one, two and three used the same date, time, and sky condition but a different set of points as input for the kriging process. Reducing the number of input points increases the area to be predicted thereby providing the proper ratio to be used for selecting the number of points to predict illuminance levels. Scenario four is used to test the accuracy of the kriging prediction under extreme climatic conditions.

RESULT & DISCUSSION

Figure 4 shows the plot of the illuminance levels by simulating a full mesh along with a typical Radiance simulation. The result of this simulation was used as a base case to compare with scenarios one, two and three. The result showed that average illuminance is 225.16 lux.

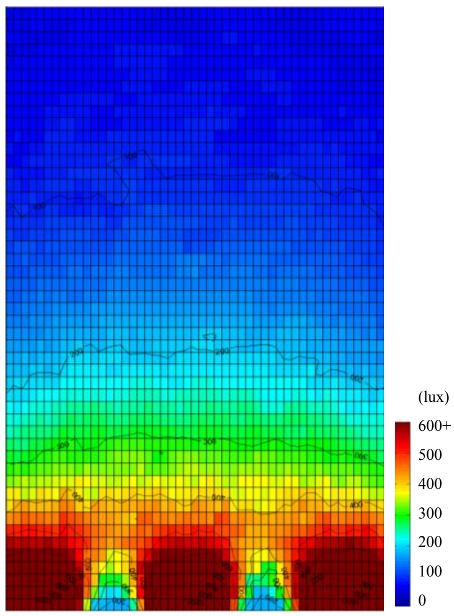

Figure 4 Full grid illuminance plot (Base Case, June21, with Radiance)

Figure 5 is the illuminance plot for scenario one, which used 117 points to predict illuminance levels.

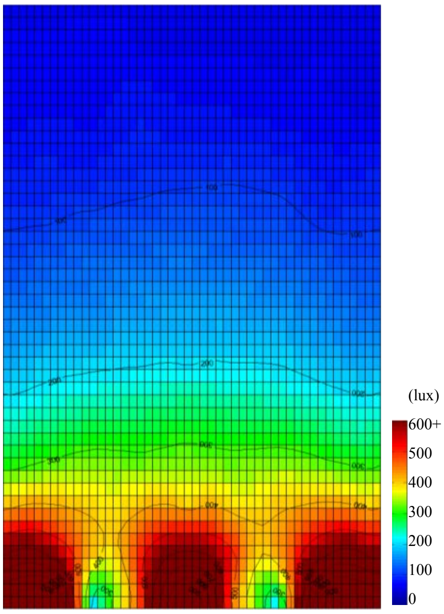

Figure 5 Kriging interpolated illuminance plot (scenario one, June21)

The result showed that average illuminance is 222.95 lux. The average illuminance difference between the base case and scenario one is 2.21 lux, which is 0.98%. Table 3 shows the overall comparison between the base case and scenario one.

Table 3 Kriging result – June 21

	Base Case	*Scenario One*	*Diff.*
Maximum	1150.39	1106.10	3.85%
Minimum	54.29	57.69	6.27%
Average	225.16	222.95	0.98%

Next, an error analysis was conducted to determine the increase in deviation if a smaller number of input points are used. Therefore, two more cases were tested each using a different number of input points - 35 points and 12 points, with ratios of 4.68% and 1.48%, respectively, compared to the base case. Figure 6 shows the plot of Kriging predicted illuminance levels with differing numbers of input points and Figure 7 shows the deviation of Kriging prediction from the base case. In scenario two, the 35-points case, under-estimation occurs significantly near the window locations and over-estimation occurs at in-between locations. In scenario three, with 12 points, over-estimation occurs

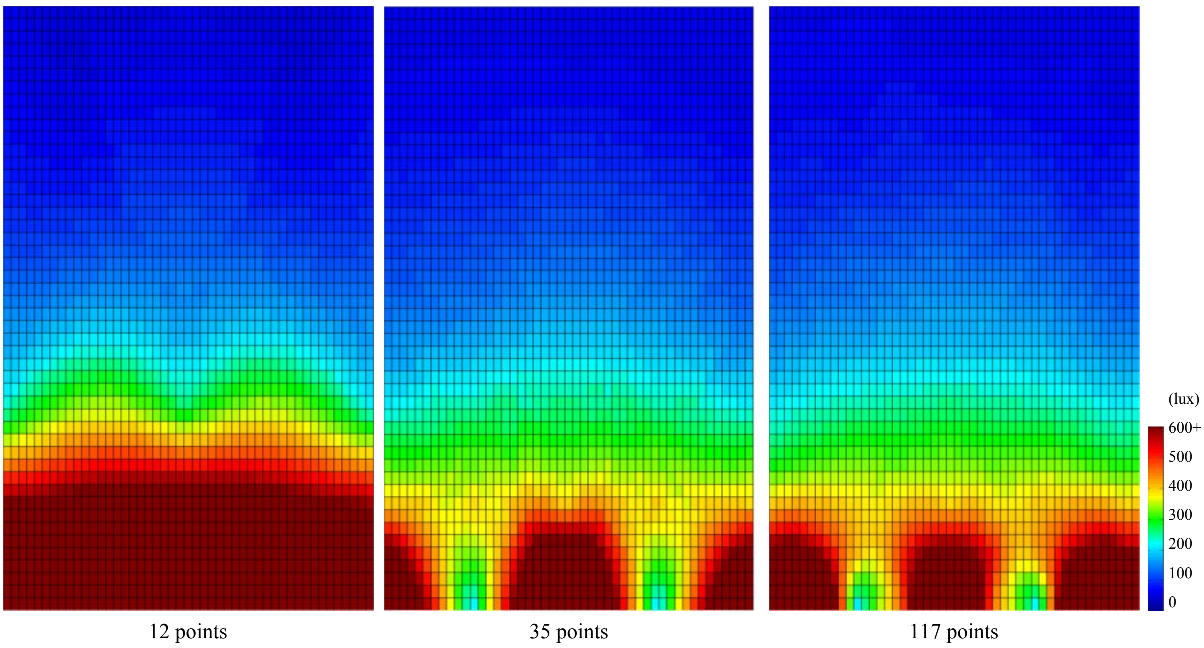

Figure 6 Kriging results with different number of input points for June21

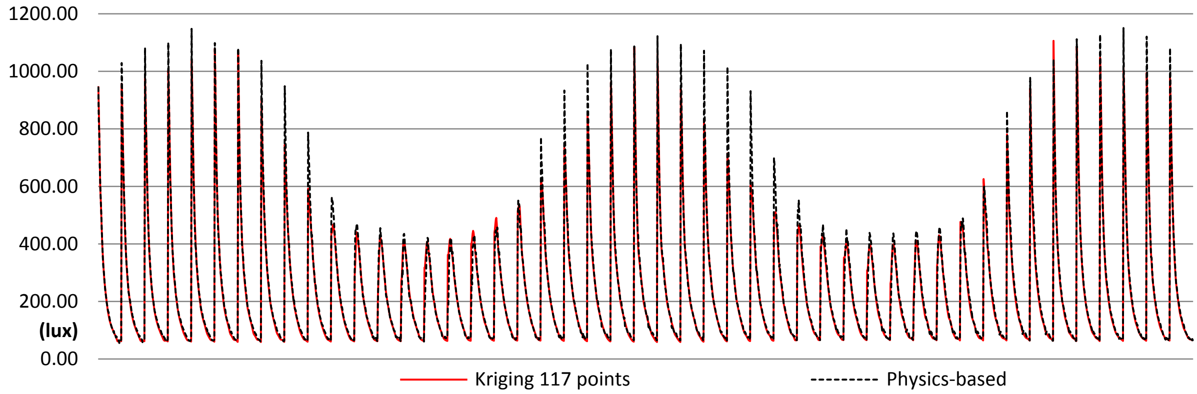

Figure 7 Kriging case of 117 point scenario with physics-based prediction for all data points (June21)

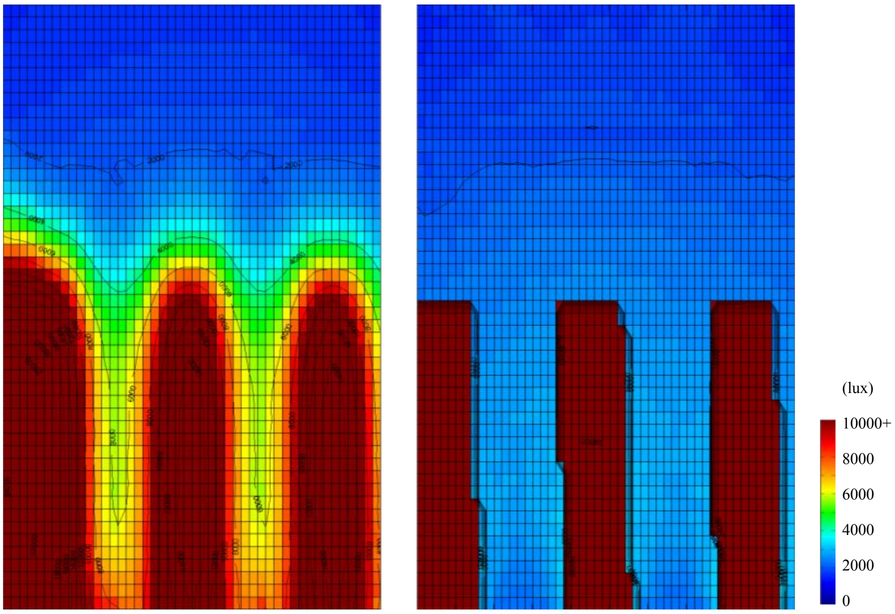

Figure 8 Kriging interpolated value (left) and physics-based based case value (right), Dec 21

even more significantly between windows and the affected area increases deeper into the space than the 35-points case. However, increasing point density did not affect the deeper areas in the room, which is relatively far from the complex window area.

Table 4 Error analysis for different input point numbers for June 21

Scenario	Number of points	%	Average deviation	%
Base case	2500		225.17	
1	117	4.68	222.95	-0.98
2	37	1.48	218.62	-2.90
3	17	0.68	301.33	34.27

Full meshed radiance simulation took about 25 seconds on a standard personal computer, which is a longer computational time compared to any Kriging scenario, which takes about 13-19 seconds. Scenarios 1 and 2 show reasonable agreement with the radiance results but saved 24% and 40%, respectively, of simulation time compared to the base case.

The next test conducted used a different date. The base case was simulated using the same boundary conditions except the date was changed from June 21st to December 21st. Figure 8 shows the result between scenario four (Kriging interpolation with 117 points) and the base case.

Table 5 Kriging results for December 21

	Base Case	*Scenario 1*	*Diff*
Maximum	25,075.50	24,199.05	3.50%
Minimum	1,447.85	1,527.50	5.50%
Average	7,766.16	7,351.24	5.34%

Results show that the difference in average illuminance increased compare to the June 21st test. The base case result shows that the average illuminance is 7766.163 lux, which is a difference of 414.914 lux (5.34 %) from the Kriging prediction. Table 5 shows the overall comparison between the base case and scenario 1 for December 21st.

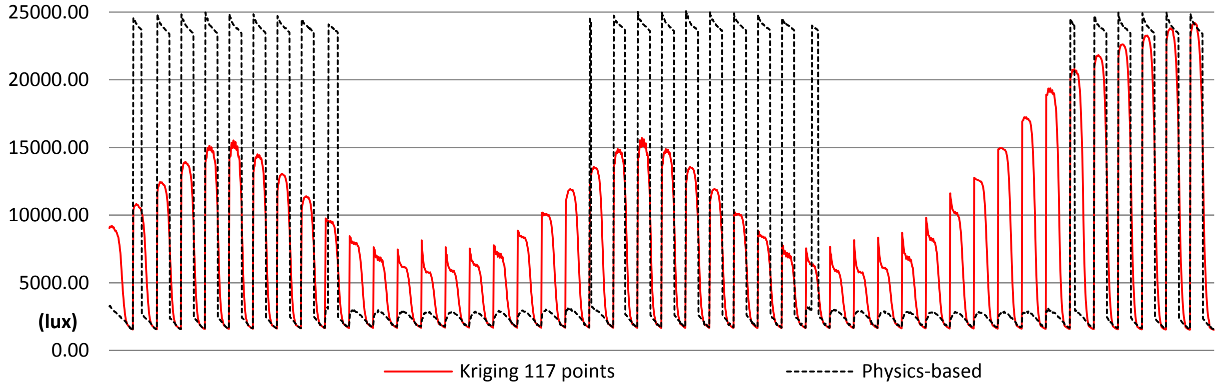

Figure 9 Kriging case of 117 point scenario with physics-based prediction for all data points (Dec 21)

DISCUSSION

This paper proposed a new method for predicting illuminance conditions without a full advanced lighting simulation. The Kriging method was utilized to predict unknown nearby location values by interpolating the significantly smaller number of input data than is required for the full radiance simulation.

The overall result shows that the average illuminance between Radiance and Kriging were within a reasonable error range (0.98-5.34%). In the June tests, the number of input points can be reduced to 37 points while still being able to produce a reasonable match with Radiance simulation results. With the December test, results show that in extreme conditions, when light contrast is significant, the Kriging prediction produces a bigger error compared to the June cases and suggests that a finer grid of points is needed for higher prediction accuracy.

Preliminary analysis regarding computing time between Radiance and Kriging demonstrates that the proposed method can reduce calculation time by 40% compared to a typical simulation. Reduction in computing time can be even greater if the analysis requires a full year, hourly illuminance calculation. However, computing time reduction may vary with complexity of the geometry as well as other unknown variables. Therefore, a more accurate determination of computational efficiency requires further investigation.

This paper was the first attempt to uncover possibilities of utilizing the Kriging method in Building Simulation. As an initial investigation, the paper used a Kriging model to demonstrate the possibility of determining a better indoor illuminance level compared to the current daylight factor method, while also reducing computing time when compared to a full advanced daylighting simulation. In summary, following are the initial developments and additional research proposed by this paper:

- A more advance kriging model is needed to improve the prediction.
- A density test of Kriging input points for a complex shape building: more data points for complex portions and less data for simple portions.
- Negotiation between accuracy and computational expense for the complex object.
- A comprehensive analysis for the variation of Kriging accuracy due to the wide range of solar conditions in other periods of a full year.
- Uncertainty quantification comparison between the Kriging method and the Daylight Factor method in energy consumption.

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