Real-Time Light Simulation Methodology for Expedited Comparison and Optimization Studies through Agent-Based Photon Modelling

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Abstract

Designing for receiving ample daylight is an integral part of an Architect's early design framework. However, conventional Daylight Simulation tools for daylight analyses are time taking due to their dependency on external simulation engines. Moreover, several inputs are required to set up the simulation process. While this maybe useful for analytical studies, conventional daylight analysis workflows in early-phase design decisions, for multiple design iterations can be cumbersome and require running thousands of test cases to optimize a design. This research proposes a step-by-step method for utilizing light simulation as a metric for optimization that uses agent-based modelling of photon particles to generate instantaneous daylight illumination results for comparative and real-time directional analysis of early-phase design iterations. This algorithm removes external dependencies of simulation engines and runs instantaneously. This enables quick performance optimization for real time design decision making, and also allows using real- time daylight impact assessment in generative design studies. It also consists of a front-end interface for non- intuitive users to perform comparative studies with ease. To demonstrate the speed and effortlessness of daylight evaluation using this methodology, a façade design is explored using multiple geometrical inputs to find an optimized solution with real-time directional and comparative feedback. It has been observed that the proposed methodology is near-instantaneous as compared to conventional simulation methods for iterative design optimization.

Key Innovations

- A unique methodology to run instantaneous comparative daylighting studies where options are to be "rankable" and absolute performance feedback is unnecessary.
- Agent based method allows parallel processing for real-time feedback assessment, giving instantaneous simulation results even while running on the CPU.
- First study in the state of the art to allow multiple materials in agent-based performance simulations.
- Rapid comparison using this method allows usage of daylighting in generative design studies.

Practical Implications

Simulations for tasks involving comparative evaluation, optimization, etc. - are time taking. They require external simulation-engine dependencies and take a while to return results. While the required tasks are comparative in nature, and multiple design options are to be rapidly evaluated and ranked, the performance evaluation process must be expedited (almost real-time), easy to setup (non-intuitive) and computationally non-intensive. In such scenarios, it is also sufficient if results are not absolute but rather comparative and "rankable". Agent Based Modelling (ABMs) is an approach to model systems composed of autonomous and interacting agents that have a set of policies or behavioural rules and are constrained in an environment. Parallels can be drawn between ABM and the properties of light particles (Photons). This research project explores if ABM can be used to emulate light behaviour to an extent that it is possible to compare multiple design options and make daylight performance directed design decisions, in an expedited way and in real-time.

Introduction

Daylight Simulations for incoming daylight quantity analyses - especially for tasks involving comparative evaluation, optimization, generative design etc. - are time taking, as evaluation is done iteratively through simulations for multiple iterations over a large design sample space. This is extremely costly in terms of computing costs and time. There are also external simulation-engine dependencies and a number of inputs and steps to setup the simulation process which might take a while to evaluateand return results for a given design iteration. While performance evaluation and especially directional evaluation, comparative evaluation and evaluation for generative design studies need to be done rapidly and close to real-time - for multiple design iterations in early-phase design decision making, the conventional analysis workflows are extremely time taking.

This article proposes a methodology, for utilizing light simulation as a metric for optimization, comparative studiesand generative design studies which uses agent-based modeling of photon particles, mimicking their properties using certain light-like policies, to generate instantaneous daylight performance results for comparative and qualitative analysis of architectural spaces.

The algorithm removes external dependencies of simulationengines, runs on CPU (can be run in GPU for faster and heavier results), and since it works with direct geometry collision and particle-based methods, it works with non- orthogonal and non-linear geometries as well. It also doesn't require any simulation recipe preparation and runs directly on input meshes.

Curved input geometries are accepted, and a large analysis test mesh can also be executed in real-time using multithreading of particle groups. This creates excellent scenarios for real-time design decision-making, quick performance optimization, etc.

A custom Genetic Algorithm (GA) is used for optimization,in which fitness graph is visualized real-time as well for post-optimization design decision making. A front end interface is developed for ease of use for non-intuitive users,which is described further in the final outcome on Page-5.

Literature review

Over the past few years, several architects, building performance analysts and researchers have developed several tools to predict the performance of daylight inside a building. Several algorithms have been used to predict daylight and there have been at least 50 different simulation tools invented to predict this. Split-flux, Radiosity, Raytracing, Path tracing and Photon Mapping and some of the methods used for Light Transportation Algorithms (LTA) (Ayoub, 2020).

Light Simulation Method

Radiosity provides more accurate results than Split-Flux (Yoon, 2014) as it can calculate inter-reflectivity between surfaces (Reinhart, 2018) unlike Split-Flux that only calculates absorption, reflection and refraction based on surface properties. Though several simulation tools Like DOE-2, Ecotect, etc. are based on Radiosity (Ayoub, 2020), the results are still not very dependable as it does not factor for specularity and transparency of materials. Raytracing and Path Tracing on the other hand are more unbiased and accurate as they handle various optical properties and can be used for complex spaces. They require intense computational power to calculate every ray-tracing interaction. These work well for simple RGB domains but are not suitable for complex systems that involve fluorescence, iridescence, and spectral rendering (Ayoub, 2020). Alternatively, Photon Mapping is memory efficient, can model light through transparent materials, and handle complex scenarios without bias through progressive photon mapping (Jensen, 2001). This method has no patent and its possibilities can be explored through various simulation engines (Jensen, 2000).

Agent-based Modelling

Agent-Based Modelling (ABM) is an approach to model systems composed of autonomous and interacting agents (Macal, 2010). The term agent could be defined as “a computer system, situated in some environment, that's capable of flexible autonomous action in order to meet its design objectives” (Jennings, 1998). The behaviors of agents are usually described with simple rules. ABM are applied in various domains and disciplines, including biology, epidemiology, economics, social sciences, etc. In building science, applications include simulating human behaviours to assist buildingsystems control (Mo, 2003), to analyse crowd behaviour in architecture (Feng, 2016), or to help with generative design approaches such as generating spatial layout (Veloso, 2020). The calculation efficiency of ABM could be extremely improved by replacing traditional CPU clusters with Graphics Processing Units(GPU) (Shen, 2011). There are but few examples that use ABM to simulate building performance, especially daylight. However, it is possible to borrow the concept of ABM, model photon particles which interactwith the building environment, and achieve the analysis of light conditions on the working surface.

The analysis grid was divided into a low-resolution grid of 10 x 10. In his grid, each square has 100 sample points which will be targeted for 100 agents. This equals to a total of 10,000 photons. Point in time daylight factor metric is used to calculate optimum daylight as our aim is to help designers in an iterative study for which a comparative value is enough and absolute value is not required. While comparing this to Ladybug, which is a radiance-based simulation tool, a shoe box model was created where point in time daylight factor was used to select between 5 different façade options. The entire process took 15 minutes. When the same process was repeated with agent based simulation, we got the same design option and was completed in 3 minutes proving that the simulation is near instantaneous.

Design Optimization

Optimization problem (mathematical optimization), can be represented in the following way:

Given: a function f: A → R from some set A to the real numbers;

Sought: an element x0 $\in$ A such that f(x0) $\leqslant$ f(x) or f(x0) $\geqslant$ f(x) for all x $\in$ A

But for design problems which are mostly NP-hardness, rather than seeking an optimal solution, we are usually pursuing a relatively good solution. Therefore, heuristic algorithms are used more frequently to solve design optimization problems. The objective of a heuristic algorithm is to produce a solution in a reasonable time frame that is good enough for solving the problem at hand. This solution may not be not necessarily the best of all the solutions to this problem. Genetic Algorithm(GA) and Simulated Annealing(SA) are commonly used as heuristic approaches for solving facade design optimization problems based on light simulation (Torres, 2007 and Gagne 2010). Some grasshopper pluginssuch as Octopus based on GA show good performance as optimization tools (Shahbazi, 2019). Moreover, the optimization process for design problem also brings up requirements for the simulation tools:

Real time feedback:

Take Octopus as an example, the optimizer takes a fitness value as the optimization target and keeps adjusting the input genes to minimize/maximize the fitness. In this case, for a desired optimization process, the simulation should give a fitness feedback fast enough in real time.

Geometry adaption:

For facade design problems, it also requires the simulation tools to be sensitive to different geometry types including curved surfaces.

Evaluation Tool

The overall workflow of this methodology can be seen in Figure 1. The simulator will take the sun angle and facade geometries to simulate the light behavior and calculate the fitness value, then the optimizer will give feedback to the input parameters to change the geometries and optimize the fitness value.

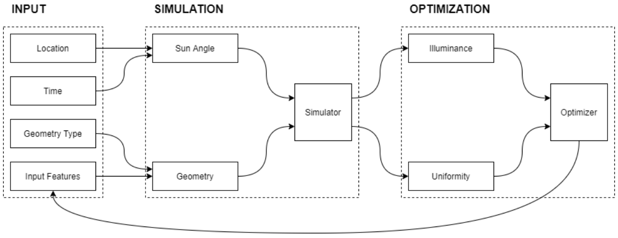


Figure 1: Workflow for the evaluation tool.

Evaluation Property

In daylight evaluation, the proper amount of illuminance and the uniformity of illuminance can be the two most critical criteria to validate a good light condition (Reinhart, 2006). Therefore, these two properties are evaluated in this tool.

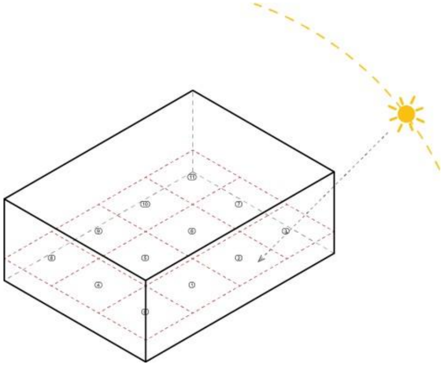


Figure 2: Evaluation Sample Grid.

- Illuminance

Illuminance is the measure of the amount of light received on the surface. It is typically expressed in lux (lm/m2).

E = Φ/A (1)

- Uniformity of illuminance

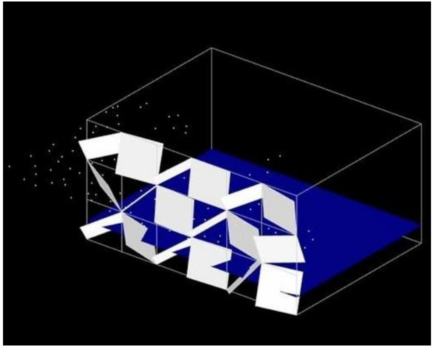
Uniform lighting allows us to perceive the environment continuously without sudden breaks caused by lighting level drops.

$U_1 = E_{min}/E_{ave}$, $U_2 = E_{min}/E_{max}$ (2)

Input

To simplify the problem, the main inputs for the light simulation are taken as the sun angle and geometry surfaces. Also the users should be able to define the working level and resolution.

- Sun Angle:



The sun angle is a vector indicating the direction of the sunlight movement. It could be calculated for any given latitude, time and season(date) that can be defined by the user.

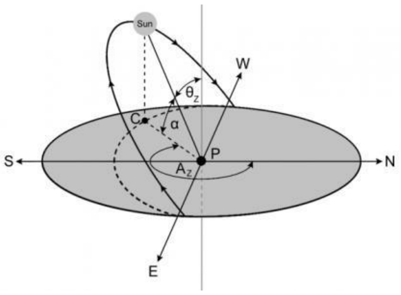


Figure 3: Sun angle calculation.

- Geometry:

Geometry surfaces are the space boundary surfaces, the facade elements or the site information. For the surface input, we design a way to represent design attributes into genes to control the geometry.

Simulation:

In the simulation process, each light photon is treated as an agent and has its own behavior against different materials. And there is a grid of cells to capture the light energy at the working level. The cell capturing more light will be mappedwith warmer color.

Initially, a group of light photons will be generated with a default energy value and initial moving direction. When each photon hits a surface, it will give different responses according to the type of the material. For example, for opaque materials, the photon will be reflected with a slight direction change according to the roughness of the material.The energy will also be partly absorbed by the surface.Finally, when the photon hits the working level, its final energy will be accumulated to the value of the cell.

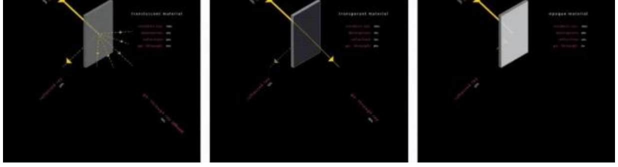


Figure 4: Diagram for photon behaviour with materials.

Figure 5: Simulation Process.

Optimization

In the optimization process we utilize the evolutionary solver from Galapagos, a plugin for Rhino-Grasshopper. The solver takes genomes and fitness as input. The genomes are taken as the parameters which are control the geometry, and the fitness is taken as an integrated value combining illuminance and uniformity.

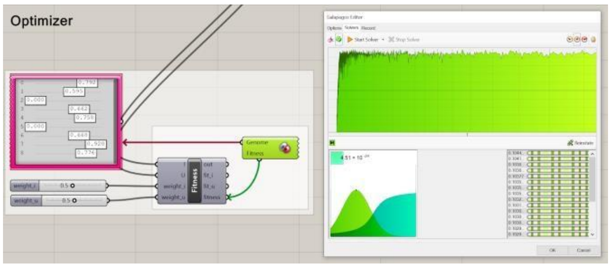


Figure 6: Optimization Component.

Fitness Function:

According to the evaluation properties defined before, thereare two objectives: illuminance and uniformity. They canbe calculated from the values of the cells. To simplify the problem, we do not use the original formulas in architectural physics and change them into the following calculation method:

- Illuminance: Average of cell values.

$I = 1/N\ (x_1 + . . . + x_N)$ (3)

- Uniformity: To avoid extremely small values for this objective (since Emin will sometimes become 0), it is changed from Emin/Emax to negative standard deviation of the cell values.

$$U = -\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \quad (4)$$

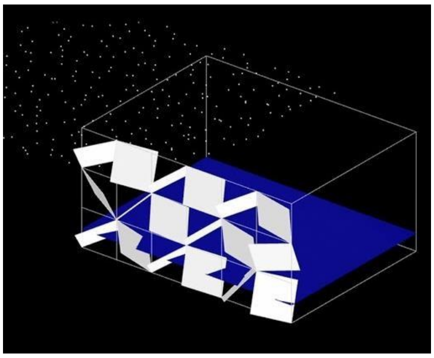
- After we get these two objectives, we need to integrate them into a single fitness value. Therefore, we normalize the two objectives with sigmoid function and combine them with a weighted method.

$$fitness = w_I * sigmoid(I) + w_U * sigmoid(I) \quad (5)$$

Analysis:

Figure 7 is the design space analysis for the optimization. The abscissa is the 1-dimension feature representing the genomes compressed by dimension reduction tools. The ordinate is the fitness value. The red line indicates the illuminance and the blue line indicates the uniformity. There is an opposite relationship between the two properties. And the yellow line is the fitness integratingboth properties.

There are three representative examples of the geometry options. Example A has high uniformity but the illuminance is low; Example B has high illuminance while the uniformity performance is bad. In the optimization, we are pursuing an output like Example C which has both high illuminance and uniformity and makes for good interiorlight condition.



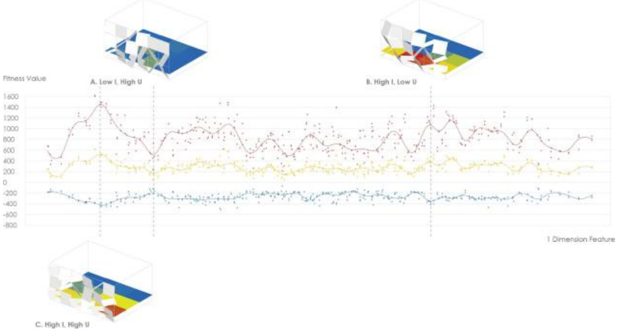


Figure 7: Design Space.

Application

The methodology can be applied to various scenarios of light-based design optimization problems. In this paper, we will take the design process of a façade system as an example.

To evaluate a facade system which is responsive to the exterior light environment, the input geometry is not fixed and changes according to the light input. Therefore, this example is suitable for testing this methodology that integrates both simulation and optimization.

Figure 8 shows the overall steps for designing a responsive facade system. There are generally two steps, unit design and distribution design. The unit design is to find out a proper geometry and transformation mechanism. The distribution design is to figure out the right scale and distribution. This chapter will show how the evaluation assists the design decision.

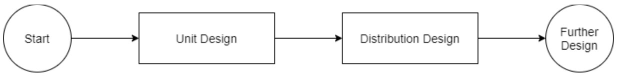


Figure 8: Responsive façade system design process.

Unit Design

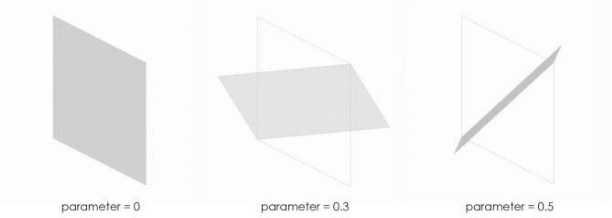
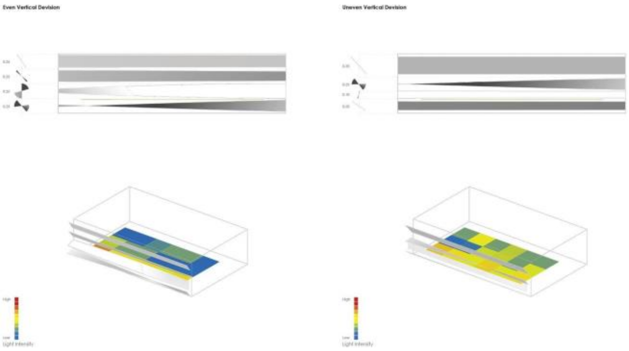


Figure 9: Geometry parameters

In the unit design, the input parameters are numbers rangingfrom 0 to 1 which control the transformation of each geometry.



Firstly, a group of simple geometries with flipping, rotation and bending transformations are tested with a certain sun angle input. After the optimization is run, all sets of geometries with the best positions are found. By comparing the final fitness value, we can infer that horizontal rotation and diagonal rotation work better in balancing the light illuminance and uniformity.

Therefore, more geometries within these two categories are developed. In the second iteration, the evaluation is more thorough. By evaluating the behaviors through time, it givesa better vision of how the geometry reacts with different sun angles. In Figure 11, the red line shows that the type 5 with horizontal twisted panels works better than other types for all periods of time, as it could handle a large range of sunlight angles.

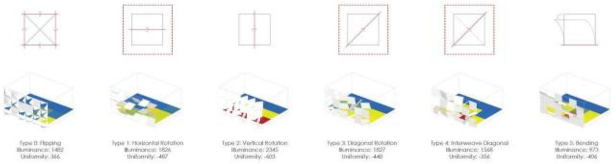


Figure 10: The first iteration of the unit design.

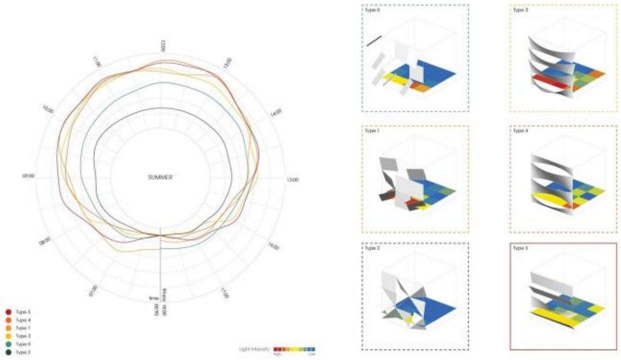


Figure 11: The second iteration of the unit design.

Distribution Design

To evaluate the scale of distribution, different types of divisions within a room scale were tested. Figure 13 shows that options with less vertical divisions and 2 to 4 horizontaldivisions behave better.

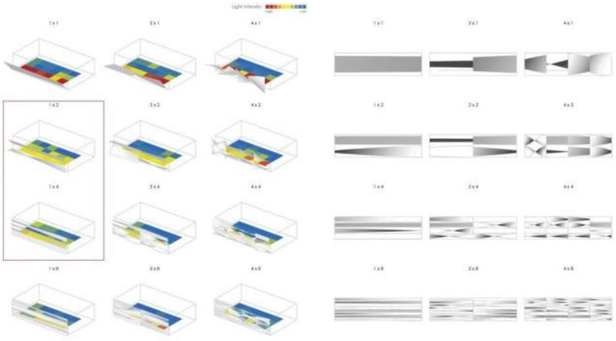


Figure 12: Scale analysis.

Figure 13: Distribution analysis.

Also, the vertical division can be weighted. In this step, the input parameters are changed into the vertical weights, which control the vertical proportion of each unit. It shows that uneven distribution can improve the light behaviour.

Final Outcome

This methodology with light simulation and optimization is flexible to adjust input parameters during the design process and gives quantifiable standards for comparing design options. In this example process, the designer still needs to come up with design choices by himself, where the evaluation is just a helper for decision making. However,by alternating the input parameters and the way to define geometries, it could also be applied in other kinds of design processes, in near instant run-time.

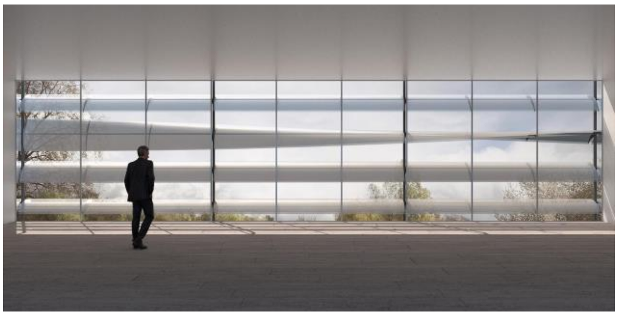
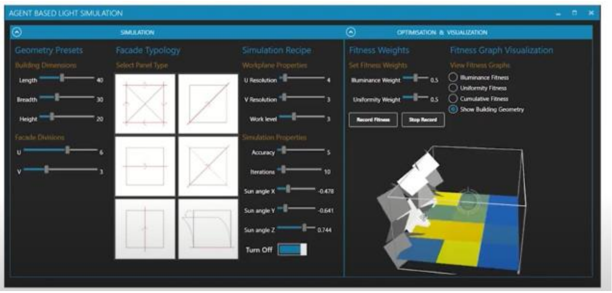


Figure 14: Final Design Outcome.

User Interface

A custom user interface is developed to showcase how non- intuitive users can utilize this methodology for comparative and optimization studies. The user interface is developed as a proof of concept for demonstrating the ease of which such a method cab be embedded in any design platform or software, for easy performative design decision making, where absolute accurate results are not required, but rathercomparative and real-time directional feedback is suffice.

The UI for the current project implementation of the algorithm is made within grasshopper, using the HumanUI plugin Figure 15 shows the overall layout of the UI.



Length 40
Breadth 30
Height 20
U 6
V 3
U Resolution 4
V Resolution 3
Work level 3
Accuracy 5
Iterations 10
Sun angle X -0.478
Sun angle Y -0.641
Sun angle Z 0.744
Turn Off
Illuminance Weight 0.5
Uniformity Weight 0.5
○ Illuminance Fitness
○ Uniformity Fitness
○ Cumulative Fitness
● Show Building Geometry

Figure 15: Light simulation for façade optimization – Front-end UI

Conclusion

With this agent-based algorithm, we can simulate the light behaviour with bordering accuracy and fast calculation. Given that there are already plenty of mature light simulation tools in the field, we made a comparison between this tool and an industry standard tool – ladybug - in grasshopper. We were able to achieve near instantaneous results with the proposed methodology as compared to Ladybug, on different computers with varying computational power. It successfully depicts how light behaves with a certain geometry input and gives adequate results for comparative studies at an extremely expedited rate. Though the results are not as accurate as ladybug, the running time is very short, which is almost real-time which is suffice for early-phase directional feedback. Also, the input settings can be much simpler than other tools and it can take any surface type objects as the geometry input. These benefits make this simulator a very good tool in optimization problems when the optimizer needs to explore a large amount of possibilities in the design space to find the optimized solution.

This simulation algorithm can also be easily embedded into any design framework or platform, where a parametric design model is to be iterated over and an optimized choice is to be chosen quickly from a large design space. It can also be used with generative design studies which require instantaneous feedback giving fitness functions which would otherwise not be possible with conventional simulation tools. This methodology also removes the need for external simulation engine and portrays a superior level of interoperability.

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Nomenclature

1. E = illuminance(lux), Φ = luminous flux, A = area
2. U = uniformity of illuminance, E_{min} = minimum illuminance (lux), E_{max} = maximum illuminance (lux), E_{ave} = Average illuminance (lux)
3. *I* = illuminance (defined in the tool), N = No. of cells, x = value of each cell
4. U = uniformity (defined in tool), N = No. of cells, x = value of each cell
5. I = Illuminance, U = Uniformity, wI = weight of illuminance, w_u = weight of uniformity

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