APPLYING CLIMATE-BASED DAYLIGHT MODELING (CBDM) FOR A MACRO SCALE MASTER PLAN DESIGN CASE STUDY: THE GREAT CITY IN CHINA

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ABSTRACT

Climate-Based Daylight Modelling (CBDM) is a methodology that allows the prediction of several measures of daylight using the sky condition from location specific meteorological data. CBDM was originally used as a means for predicting indoor daylight availability and intensity. Since the scalability of the method has been proved it has been applied at different architectural scales for different studies, for example monthly cumulative irradiance and annual hourly illuminance level.

Challenges in applying a CBDM methodology to large-scale projects are the high demands of time and computational capacity. Moreover a limitation on the simulation tools' capacity regarding the number of measuring points limits the applicability of the study on large-scale projects. To extend the usage of CBDM to large-scale projects, this paper introduces an automated method for using multiple systems simultaneously and thus benefit from the advantages of cloud computing. This enables the application of climate-based daylight modelling for large-scale projects within a reasonable time.

To illustrate its applicability, this paper selects a real project as a case study to describe how the method has been used in the application of CBDM for evaluating master plan options for a new urban design project in China during the conceptual design phase.

KEYWORDS

Climate Based Daylight Modelling, Macro Scale Simulation, Design Automation, Cloud Computing

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INTRODUCTION

Running analytical studies during the early stages of design can be both informative (informing the design process), and confirmative (code compliance). Recent developments in computational simulation enable the sharing of in-depth knowledge for improved performative design and the possibility for conducting various analyses at the building level. On the one hand, the greater the scale of the project, the larger the impact of the improvement; on the other hand, the larger the scale of the project, the harder it is to run and implement the studies.

Among the different domains for achieving high performance design with computational simulation is the lighting. Lighting energy consumption is reported as comprising 27% of total energy use in residential buildings, increasing to 51% of total energy use in commercial buildings (Building Technologies Program 2012). Therefore, designing the city to allow appropriate levels of natural daylight is essential for ensuring that the performance goals of the project are achieved.

Despite the great potential for the design benefits from daylighting simulation, there are multiple difficulties in applying the studies to large scale projects. For this reason, rule of thumb and simplified methods are usually used to study large scale projects. This paper shows the limitations of sunlight hours as a simplified method versus Daylight Autonomy (DA) as a Climate Based Daylight Measure (CBDM).

In regard to the technical challenges of applying a DA study, the paper identifies the difficulties and proposes a method to resolve them and implement the proposed method with a real project in China to show its robustness and ability to handle a large scale project. The case-study is a 1.3 km^2 (130 hectares) city in China named as GREAT City. The City is planned to accommodate a population of approximately 100,000 people.

METHODOLOGY

There are a number of different daylighting performance metrics that have been proposed in the past, with each having its own limitations and benefits. Reinhart et al. (2006) describe daylight factor, view to the outside, and sunlight availability as simple and frequently used quantitative daylighting performance metrics and propose climate-based daylight metrics (i.e. daylight autonomy) as the more advanced measures. Among these different measures for daylighting, this paper compares sunlight hours to daylight autonomy.

Sunlight hours, which was the required code compliance parameter for the test case project, refers to the number of hours of direct sunlight that a specified location will receive throughout a particular day (21st of December).

Daylight Autonomy (DA) is the other measure used; it is defined as the percentage of occupied hours per year, when a specified minimum illuminance level can be maintained by daylighting alone. The minimum illuminance level corresponds to the minimum physical lighting requirement which has to be maintained during the occupied hours so that a certain task can be carried out safely and without tiring the working occupant (Reinhart 2010). DA is based on Climate-Based Daylight Modelling (CBDM) (Mardaljevic 2006), which was originally used as a means to

predict indoor daylight intensity but is also applicable for other scale projects as well as urban design (Mardaljevic 2010).
Despite the potential for the design to benefit from the daylighting analysis there are multiple difficulties in applying the studies to macro-scale projects. The major hurdles can be listed as below.

1. Complex model preparation process
The process of preparing a model for a typical lighting simulation may be summarized as: 1) Exporting geometry from a CAD tool, 2) Importing geometry into simulation tools, 3) Preparing boundary conditions, 4) Setting test conditions, 5) Calling simulation engine, 6) Running the simulation, and 7) Visualizing the results. Each of the multiple stages of the simulation requires significant time and presents a high risk of error generation during and between the processes.

2. Capacity limitation of simulation tools
The daylight simulation tools currently available are not designed for macro-scale projects. For example DAYSIM is limited to a maximum number of 5,000 test points; however, the number of test points for a macro-scale planning project will most likely be more than several hundred thousand points.

3. Extensive simulation running time
The other major impediment to running macro-scale simulations is the extensive computational time required for the analytical aspects of the study. Using a typical approach, the simulation time at the scale of a city can take several days.
To overcome the limitations identified above, this paper proposes a new method as shown in Figure 1. In this method, preparing boundary conditions, setting up a primary test condition, and exporting the simulation geometry is automated within the 3D modelling tool. The governing tool modifies the test condition (if applicable), and distributes the simulations across a cloud computing system. The governing tool also collects and analyses the output data. The result is automatically imported back to the 3D modelling tool for visualization.

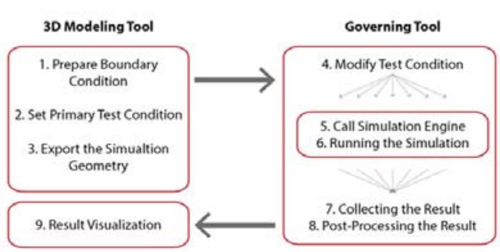

Figure 1. *Proposed simulation workflow*

An automated process, significantly, reduces the preparation time and the amount of errors. Lagios et al. (2010) describe an example of daylighting simulation automation using RhinoScript. This study uses the scripting methods based on the one of author's previous researches (Yi and Malkawi 2009) to automate the process. Scripting allows external governing and integration of the analysis tools to overcome the tools' restrictions for special studies. Finally, cloud computing can reduce the simulation time to a more reasonable period.

CASE STUDY: GREAT CITY

The case project has been given the name "GREAT City" to describe its key attributes: Green, Relational, Economical, All-encompassing, and Technological. The project description was to design a 1.3 km^2 (130 hectares) city to redefine sustainable urban living in China. The development will act as a model city to be replicated throughout China. GREAT City is planned to accommodate a population of approximately 100,000 people. Approximately 35,000 housing units will be created, with an additional 5,000 live-work units, for a density of 310 units per hectare.

As previously mentioned two daylighting criteria were analysed within the GREAT City: 1. Sunlight hours 2. Daylight Autonomy. Based on the local government's technical urban planning guide, different types of buildings need to receive a minimum number of hours of sunlight on a particular day of the year as in Table 1.

Table 1. *Minimum required hours of sunlight*

Program	*Required Sunlight hours*	*Date*
Residential	2 hours	January 21
Elderly and handicapped residential units	2 hours	December 21
Kindergarten classrooms	3 hours	December 21
Hospital patient's rooms	3 hours	December 21

In order to conduct the sunlight hours analysis, a grasshopper script was developed. Figure 2 shows the process within the script to simulate sunlight hours with the Rhino 3d modelling tool. The script reads Rhino geometries, generates the test points, calculates the number of sunlight hours for each point by calculating the intersection between the solar rays and the geometries, and finally visualizes the result. This calculation takes around 60 minutes for the GREAT City.

The script needs Rhino geometry, U size and V size to generate the test points, plus latitude of the site and day and month to generate the solar vectors. Grasshopper can convert surfaces to mesh based on U and V size. Mesh vertices define the test points for the study. For this study U size and V size were defined as 4m and 3m respectively which provide a resonably dense test grid.

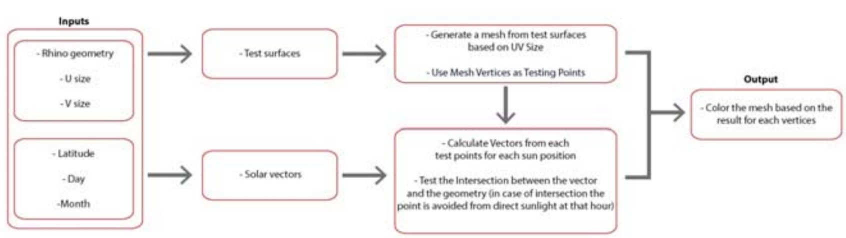

Figure 2. *Sunlight hours Grasshopper script workflow*

Following the establishment of the test points, the script uses solar vectors to calculate the vectors from each test point to the sun positions on the test day. For the next step, the script tests the intersection of each of these vectors with the building geometry. The null result is equal to one Sunlight Hour for the test point. After finishing the test for all the points, the mesh is coloured based on the number of sunlight hours.

The second criterion for light study is the Daylight Autonomy (DA). In order to conduct the DA study, several tools are used as shown in Figure 3. Grasshopper generates testing points and exports the geometry as a .rad file from Rhino. DAYSIM runs the annual lighting simulation. After the completion of the simulation a different Grasshopper script imports the processed results for visualization.

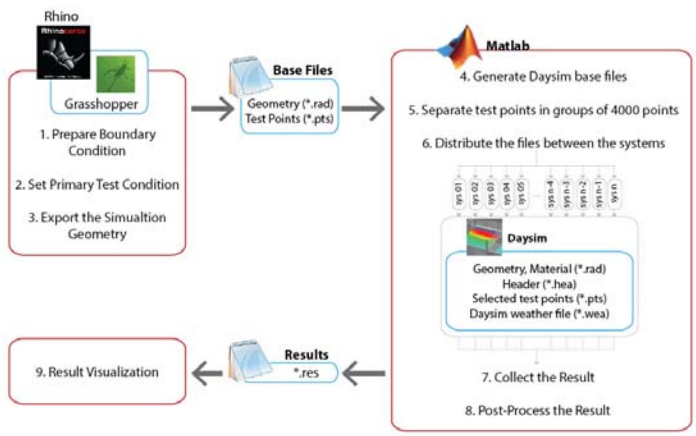

Figure 3. *Daylight autonomy simulation process*

The main challenges in conducting the daylight autonomy with DAYSIM are the limitation on the number of test points and the time for conducting simulation. As mentioned before, DAYSIM is limited to a maximum number of 5,000 test points. Moreover, the simulation for 5,000 points requires about 1.5 hours of time on a test system having 8 CPUs and 16 GB of RAM, which means that the study for GREAT City (775,00 – 800,000 points) would require more than a week of simulation time.

Due to the significant amount of time required for simulation, the opportunity to provide timely feedback for implementation into the design process is minimized. In a typical design process several quick design modifications need to be studied. Providing timely feedback from these studies is essential. To conduct the simulations at the design pace and to meet the time limitations a customized cloud computing system was established and used.

The main idea of this system is based on the potential of two available resources in architectural offices: available idle computation power, and a shared network system. Firstly, almost all of the tools that architects are using in an architectural office are single-threading tools and there is an opportunity to use other available idle CPUs for running the calculations. Secondly, there is shared memory space for architectural projects in the office that all the staff has access to.

In this workflow, MATLAB controls the process from the governing system. To start the process, a MATLAB script generates a number of batch files for each individual available CPU. These batch files are set up to control the simulation on target systems. As soon as the user executes the batch file on his system, it starts checking for simulation files to be provided by MATLAB on the shared folder. Then the batch file executes the simulation and notices the governing script after the completion of the simulation. The governing MATLAB script reads the available result and sends the next simulation to the queue on the system. The process continues until no more simulations remain. In case a user turns off his system or the script cannot find the simulation result after 2 hours from the execution, it sends the simulation to the next available system. Figure 5 illustrates the idea of cloud-computing system.

Both tests use the same simulation condition except cloud computing uses 36 CPUs on average. Figure 6 shows the time reduction between single and cloud computing, where cloud computing can reach its result about 15.76 times faster than single computing. It takes about 12.2 days to conduct the simulation using a single system whereas it takes 0.7 day with cloud simulation.

DISCUSSION

This section investigates the outcome between the two daylight studies. Figure 4 and Figure 5 show comparative results for sunlight hours and daylight autonomy studies for the entire city, and the more detailed view of the south.

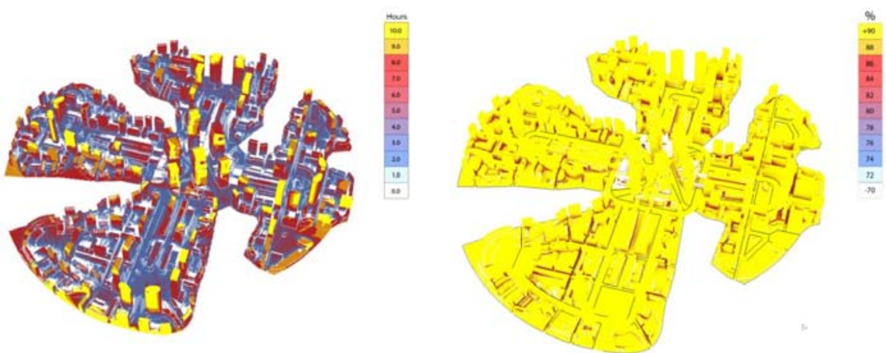

Figure 4. *All City – sunlight hours study (right) versus daylight availability (left).*

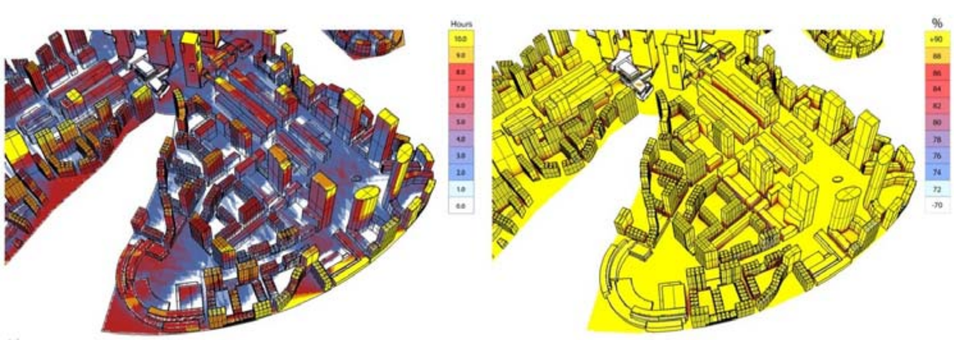

Figure 5. *South District, sunlight hours study (right) versus daylight availability (left)*

The figures show that different conclusions can be made for the same design from the two different studies; many of the areas that receive no direct sunlight on 21st December (areas coloured in white) are well daylit during the year (>= 90%). In other words sunlight hours for a specific day may not represent what is happening over the course of year.

Besides the limitations of sunlight hours method applying the code brings some side effects to the design. Based on the result of the sunlight hours study the north façade receives no sunlight hours while the east and west facades receive 5 hours of Sunlight each. In case of double loaded buildings where half of the units are located on one side (e.g. North) and half of the units are located on the other side (e.g. South), the units on the north will have no chance to receive any of the sunlight which causes limitations in the design program for the units. This fact favours the choice of east-west orientated buildings over north-south orientated one.

The result of comparative energy and daylighting simulations for two typical prototype blocks in the GREAT City facing north-south and east-west shows that the total heating and cooling load for east-west oriented prototype is on average 2% more than an identical north-south oriented prototype (Figure 6); and the daylight availability within the occupied space on the 1st floor of an east-west oriented prototype is 2% less than an identical north-south oriented prototype (Figure 7).

These studies illustrate that sunlight hours may not accomplish its intended goal in certain locations and encourage the use of climate-based daylighting measures for more accurate results.

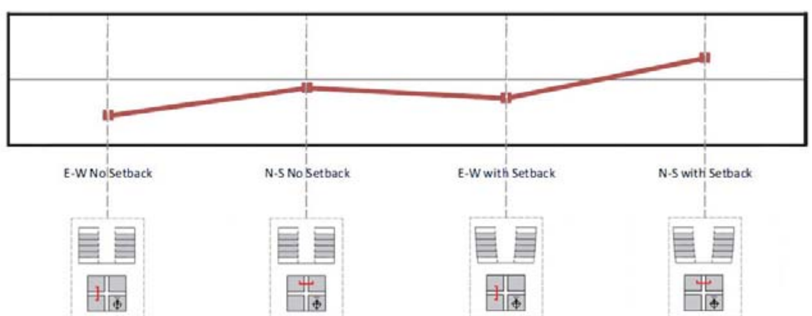

Figure 6. *Total energy use comparison for E-W and N-S oriented street prototype*

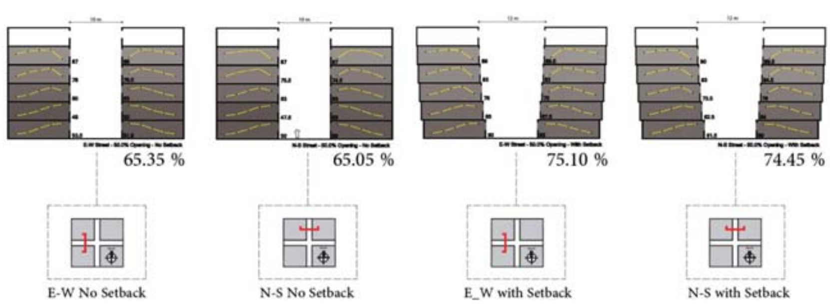

Figure 7. *Parametric daylight availability study*

CONCLUSION

The paper describes a methodology for integrating Climate Based Daylight Modeling (CBDM) for macro-scale design projects. Different lighting measurements are discussed briefly and two measures are applied: Sunlight hours (as the code requirements measure) and daylight autonomy (as the climate-based simulation method).

The paper discusses the impediments of running climate-based simulation methods for macro-scale projects and proposes a method to overcome these impediments. The method automates the simulation process and utilizes a customized cloud computing system.

A case project is selected to prove the robustness of the proposed method. The result of the study shows that applying the proposed method reduces the simulation time for daylight autonomy study from about 12 days (291.5 hours) to less than one day (18.5 hours). The significant improvement in time and automation of the process provides more timely feedback to the design team than when utilizing a conventional climate-based daylighting simulation approach.

Finally, the paper compares the results of both studies for the final design option and describes the limitations of sunlight hours versus daylight autonomy. Because of multiple limitations of sunlight hours the paper recommends using the daylight autonomy simulation for similar projects.

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