URBAN DAYLIGHT SIMULATION
CALCULATING THE DAYLIT AREA OF URBAN DESIGNS

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ABSTRACT

This paper describes the development of a new tool that allows designers to simulate and evaluate the daylight potential of urban master plan proposals. The tool is a plug-in for the Rhinoceros3D CAD modeler and follows a two-step workflow. During the initial step, hourly solar radiation levels on all facades within an urban scene are simulated based on Radiance/Daysim. During the second step, exterior radiation levels are converted into hourly interior illuminance distributions using a generalized impulse response. Climate based daylighting metrics, such as daylight autonomy, are also computed. The results yielded by the new method are carefully compared to regular and substantially more time-consuming Daysim simulations. This comparison shows that the overall daylit area in the investigated master plan matches Daysim predictions within 10%. Given its implementation into the Rhinoceros3D environment, as well as the almost instant simulation feedback, the tool may serve as a generative method for designers.

INTRODUCTION

Already more than half of the earth's population lives in urban areas and according to the United Nations and almost all of the world's future population growth is expected to take place in urban areas of developing countries [United Nations 2011]. Consequently, urban planning, especially in developing countries, constitutes a liability and opportunity for climate change mitigation as well as improvement of health and quality of life of the urban population. Within this context, daylighting is of interest because it has been linked to resource efficiency and health. Around 40% of the total energy demand in western countries is caused by buildings [DOE 2012] and with some "25% of the energy consumption of office buildings coming from electric lighting". Heating and cooling loads are obviously also greatly influenced by solar radiation [Franzetti et al. 2004]. Therefore, a smart use of the sun as a free local energy source in architecture becomes more and more essential in times of high energy prices and fossil fuel scarcity.

Traditional building performance simulation research has mainly focused on individual buildings. There are tools available to evaluate buildings during design but these tools tend to require extended calculation times when it comes to daylighting analysis. During schematic design, variants can change on an hourly basis. In order to implement an evaluation step into the design workflow, simulation speed hence becomes a key requirement for successfully using simulation tools at the urban level. Another pitfall is that handling simulation results for dozens or hundreds of buildings and stories becomes prohibitively time consuming and tedious using conventional daylighting software. Yet another difficulty constitutes that current tools require very detailed inputs, many of which are unavailable during the master-planning phase, which in turn necessitates a very experienced user capable of making suitable assumptions. On the other hand, the importance of implementing design and evaluation tools during the master plan phase is self-evident given that decisions made at this point such as building proportions and their spatial interrelationship, largely make or break the solar and daylight potential of the individual buildings.

For these reasons a number of researchers previously worked on urban daylighting analysis methods. Compagnon proposed a method that evaluates several sustainability metrics of urban massing models based on cumulative incident facade irradiations [Compagnon 2004]. He proposed suitable radiation ranges for passive solar heating, photovoltaic (PV), solar-hot-water (SHW) and daylighting in the Swiss context. He further developed a diagram to display the relationship between façade orientation and solar potential. The strength of this approach is that an entire district can be quantitatively evaluated by one diagram and one number [Compagnon 2004].

While the suitability of installing PV and - to a degree - SHW can be evaluated based on cumulative radiation levels, the approach is less suitable when judging the potential for interior daylighting. The approach neglects the high dependency of reliable daylight simulations on the specificity of a building's geometry.

Building on this previous work, this study hence presents two innovations:

- An optimized work flow that automates the process of setting up an urban simulation and visualizing the results.
- A methodology that translates outside hourly radiation data falling on facades into interior illuminance distributions to reduce computational effort.

The latter method is compared to traditional detailed daylight simulations using Daysim/Radiance.

METHODOLOGY

Urban Daylight Design Metric:

The main objective of this study was to create an optimized design workflow that evaluates and optimizes urban designs based on their daylight performance. The effort required to set-up and run a simulation therefore had to be largely reduced. A secondary goal was to make the workflow accessible to architects. To satisfy the latter criterion, the authors developed a method that provides both summary results for a building ensemble and detailed visual feedback so that underperforming areas of a design can be easily located, assuming that the information is required to use the tool not only for analysis and post rationalization but also as an interactive design tool.

Thus, the tool allows an iterative process, whereby relevant relationships between good performance and shape can be studied. Along with other key architectural considerations, they can then be incorporated in a final massing model. It is especially important to mention that while developing proportion and layout of urban form, it is less relevant to localize photovoltaic panels than optimizing for "spatial quality" such as the lighting condition of a space.

The IES Daylight Metrics Committee recently published a new metric that describes how much of a space can be considered "daylit" based on daylight autonomy simulations. According to the document the daylit area boundary is defined at the 50% daylight autonomy iso-contour line for a target illuminance of 300 lux. In other words, a location in a space is considered daylit if the illuminance due to daylight is above 300 lux for half of the occupied time in the year, nominally considered to be daily from 8AM to 6PM. The procedure has the dual advantage that, on the one hand it can be condensed into a single, meaningful number, i.e. "70% of a design variant's area is daylit." On the other hand it can also be displayed for each sensor individually to highlight areas that are underperforming. This mode of reporting relates directly to the built geometry and becomes thus a readable piece of information for designers. Daylight autonomy simulations can also be interpreted as hourly on/off schedules for artificial lighting. For this study occupancy schedules were configured so that every hour with non-vanishing outside daylighting levels was considered occupied in order to evaluate the daylight potential of a design.

Simulation Environment:

The CAD modeler Rhinoceros 3D was chosen as the underlying CAD environment of this work because this tool is widely used among architecture firms and schools with a strong emphasis on design excellence and computation [McNeel 2010]. The authors' group also previously developed a series of environmental performance tools within Rhino and Grasshopper, which initially helped to quickly advance the project [Lagios, Niemasz and Reinhart 2010]. All simulations were performed on a recent Macbook Pro with an Intel I7 chipset running Windows 7 64Bit.

Workflow:

The overall structure of the program is as follows: Rhinoceros/Grasshopper is used to generate and/or manipulate geometry. The geometric information (3D model and sensor point files) is then exported in the Radiance/Daysim format. Then a script takes over and builds up the simulation input files and executes the exterior simulations. Once this step is completed, Rhinoceros/Grasshopper takes the computed results back and estimates the interior illuminance values as explained below. Finally, the daylight autonomy results are color-mapped onto the input geometry for display.

The 3D model and geometric simplifications:

To study the impact of the morphology of a building in relation to its context, the buildings are represented by their enclosing envelope. The following architectural assumptions are made:

The geometric representation of the buildings can be simplified since the "influence of volumetric and relative building layout largely overweigh the importance or relevance of geometric detailing on building envelopes" [Compagnon 2004]. In addition, massing studies are usually very abstract geometries without detailed facade designs or fully designed interior spaces and structures.

The buildings are split up into floors. The subdivision can be generated automatically for each building by entering a floor-to-floor distance or modeled manually. Consequently, the following architectural assumptions are made: A vertical façade, a side-lit space and a story-by-story subdivision. This covers most of the building proposals. The geometry of each building envelope has to be entered as a "brep-geometry" (boundary representation). One may think of the enclosed building interior as a "light propagation zone" that takes the incident radiation of the façade as input and solves for the interior illuminance.

Despite this geometric simplification, the tool allows to take into account typological characteristics of buildings, such as schematic zoning and representation of cores. Light wells, courtyards, even maisonette sections can be considered. In addition to the geometric representation, other parameters like materialization of the context with varying facade reflectances and glazing ratios are important factors as well. However, according to Compagnon the reflectance "parameters do not directly depend on urban form and their on-site measurement in a real case study area would require a huge effort. Therefore, a constant reflectance value (typically = 0.2) is assumed, but can be adjusted" [Compagnon 2004] in the Radiance geometry file that is exported to the simulation directory.

The exterior solar radiation distribution:

The radiation distribution calculation is performed with Daysim, a dynamic Radiance-based daylight simulation software. Its physical accuracy has been demonstrated in several studies [Reinhart 2001]. It uses daylight coefficients and the Perez sky model to predict hourly illuminance or radiation values.

Ray tracing is then performed separately for each unit (building floor) in the scene. Virtual pyranometers and photometers are placed as a horizontal band around the building façade with an offset of 1cm and an inter-sensor distance ranging form 20cm to 100cm. Each point represents a patch of the size of the inter-sensor distance times the floor height. The irradiation is assumed to be constant throughout that patch. This calculation step yields hourly data for each sensor in lux or watt. The information can be studied to predict the solar heating potential or the possibility of overheating.

Generalized light propagation algorithm:

The search for an efficient method to compute light propagation in a space is the core of this study. In order to establish a correlation that is valid for all possible scenarios and climates, all received light has to be diffused at the facade. This is a drastic simplification since it completely eliminates direct radiation in the interior distribution. Most significantly, low sun angles that would involve a deep solar penetration into the space cannot be taken into account in this approach. A justification for the approach is that - due to glare issues –building occupants necessarily close a manually controlled blind system once a larger amount of direct solar radiation is incident on a façade. The simulation error due to the simplification is hence largely contained to hours with low radiation exposure of the facades. The new method includes a dynamic

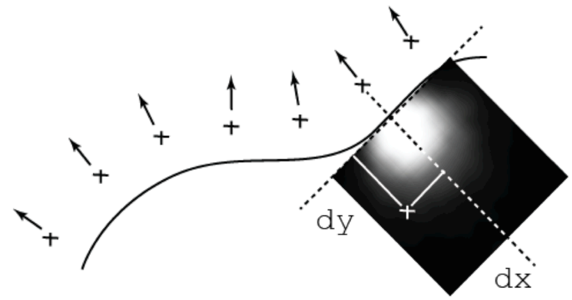

Figure 1 Graphic representation of the dataset and the geometric relationship between façade and work-plane sensors

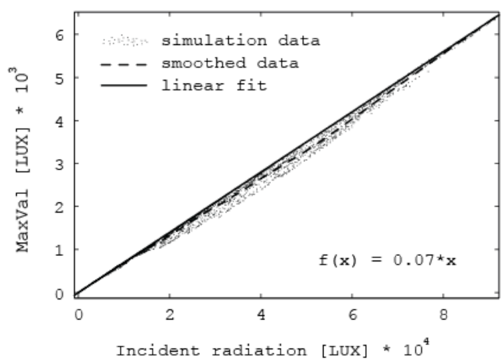

Figure 2 Correlation

blind system that becomes effective at a user defined radiation threshold. To predict the daylight potential a generalized façade with a maximum aperture had to be defined. A typical double glazed window has a visual transmission of 60% to 80%. To resemble a fully glazed façade with mullions and other structural elements the visual transmission of the entire façade was assumed to be at 50%. The 50% were also seen as a handy value that would facilitate later adjustment. The tool allows manipulating this value by a simple scaling factor.

During the development of the correlation based light distribution algorithm, several different approaches were tested. Early versions worked with a 3D fitting function. The function returned a local illuminance value when façade radiation and node-façade distance were passed as arguments. This approach was not satisfactory since it could only compute light propagation perpendicular to the facade. It limited the possible geometries to boxes with 90 degree corner angles. However, this approach yielded promising results and proved that a correlation of incident radiation and interior illuminance was possible. In order to remove the limitations of the perpendicular,

Figure 3 Forms and dimensions [m]

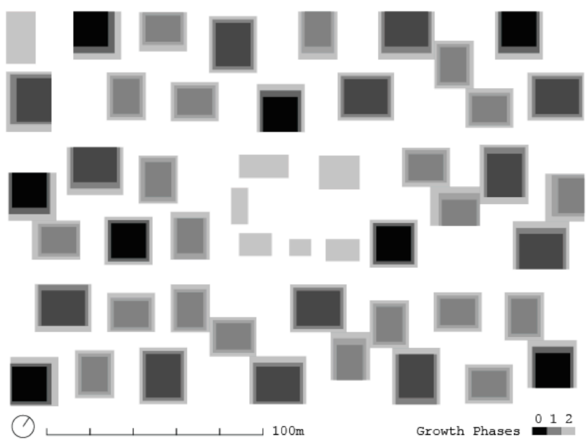

Figure 4 "Werkbundsiedlung" massing in three different iterative stages: Floor Space Index: 1.2, 2.0 and 2.5

vector based light propagation, a matrix as a lookup table was tested. The table consisted of a three dimensional matrix (x, y and incident radiation). The x and y dimensions describe the geometric relationship between façade sensor and interior work-plane sensor. This allows estimating the interior illuminance in a 180-degree view angle within the bounds of the provided data. In contrast to the fitting function, which works with just the inter-sensor distance, the data look-up approach requires a more complex geometric calculation. At each façade sensor, a local coordinate system, which is aligned with the inverse of the sensor normal, has to be established. This is analogous to rotating the light propagation dataset to align it with the tangent of the façade (Figure 1). Then the arguments x, y, and the incident radiation are passed to a function that looks up the closest data points and interpolates in-between them.

To reduce the computational cost, the three-dimensional interpolation process was replaced by a two dimensional dataset that is idealized by a linear correlation between the incident solar radiation and the maximum illuminance value inside. This correlation is shown in Figure 2 (For the watt-lux correlation the formula's slope changes to 7). This procedure returns the illuminance contribution of a façade sensor for a specific work-plane sensor. The program has to iterate over every inter-sensor relationship and accumulate each contribution at the work-plane sensor. This is repeated for every "sunny" hour of the year to write out an hourly illuminance file. In order to reduce the amount of iterations, inter-sensor relationships are only computed if they are closer than 20m to each other.

Test cases:

The new method was validated with respect to detailed Radiance/Daysim simulations in three steps.

1) Influence of the climate: Different weather conditions at different locations were chosen to test their influence. The climates were: Munich, Germany [partly cloudy, lat 48.13 long 11.70], and Phoenix, Arizona [sunny, lat 33.45 long 111.98]. A square building with an edge length of 20m and 3m height was used. Each façade was equipped with a dynamic blind system with a shading coefficient of 40%. The activation threshold was set to 10,000 lux on the façade sensor. The results were compared with a classic Daysim calculation with dynamic blinds involving 14 different simulations for each possible blind combination. These 14 separate results were consolidated into one "mixed" illuminance file, to represent the actual blind behavior of the four sided space.

The results were then studied in the following way: *First*: A representative "cloudy" and "sunny" hour below the 10 klux threshold were picked to analyze the order of magnitude of the error that the diffusion of the light at the façade entails (Average of MBE and RMSE over the x-axis). *Second*: The error for an entire year was studied (Average of MBE and RMSE over the x and y axis). The mean bias error and the root mean square error for the illuminace values but also for the results yielded by the daylight autonomy metrics are presented to study their error sensitivity. *Third*: The location of the error in the room was studied.

2) Influence of the building geometry: The geometric simplifications and assumptions needed to be validated as well. To study their effect, the five geometric forms, depicted in Figure 3, were tested. For the more complex geometries with context it would have been necessary to divide the façade into many small segments with autonomous blind controls. Whereas this can be simulated easily with the new approach, it is almost impossible to do with Daysim. Therefore, the blinds were set to be constantly down resulting in a total of 50% visible transmission. This was modeled in Radiance with the "trans" material (Settings: 0 0 7 0.9 0.90.9 0.05 0 0.59 0.01). The geometric study was performed in both climates and the annual measured error for the hourly illuminance values, continuous daylight autonomy and daylit area are reported below.

3) Case study: In order to demonstrate the functionality of the new methodology in a real world application, the winning competition entry for the “Werkbundsiedlung” in Munich by Kazunari Sakamoto was selected [Busenkell 2007]. The design, which involved 130,000 m2 of built area, was abstracted, and each floor was modeled as one light-propagation zone. Zoning and occupancy types were not separately defined. Sakamoto’s design proposal, which did not undergo a stringent urban daylighting analysis, was designed according to the following principles: Sakamoto organized his design as a landscape continuum that flows through various compact point massing’s and establishes a disperse outdoor space with subtle borders between private and public [Busenkell 2007]. Therewith, Sakamoto articulated an opposing position to the closed block typology that is more common in Munich. It is particularly interesting to see how Sakamoto was able to evoke the feeling of airiness while at the same time achieving an urban density. This conflict between openness and density directly correlates to what designers are confronted with while optimizing their proposals for daylight performance. In the parametric variation study of the original design in Figure 4, it is shown how different design iterations with different spatial proportions can be compared easily with the novel method. The outdoor space is also analyzed qualitatively. In total 244 separate units/floors are evaluated per iteration. The geometry was coupled with a custom script in Grasshopper that calculates other urban design related data such as the site occupancy index, floor space index, cubic index, the number of apartments and the number of occupants on the fly. The daylight metrics are displayed in relation to the floor space index as an indicator for density of the design. Grasshopper is also used to alter the proportions of the geometry to generate three different massing’s with varying density. Afterwards multiple passes of the interior light propagation function were run to study different window-to-wall ratios. Similarly, different floor-to-floor distances or façade patterns could have been tested without recalculating the exterior radiation distribution.

The following aspects are simulated:

- Solar exposure of the facades: This is an intermediate simulation step to get the spatial daylight autonomy.
- Daylight Autonomy and determination of the daylit area: The result can be displayed in two resolutions. A summary result for each light propagation zone can be mapped on the zone geometry. This is useful for large models to generate graphics that provide an overview. If more detail is needed, the point wise results can be displayed. This is especially useful to track down underperforming areas and understand why they are insufficiently lit.
- Sun exposed hours of exterior spaces: In urban design the quality of the outdoors is as important as the interior. A derivate of the Daysim automation algorithm was developed to simulate the direct sunlight exposed hours. This is regarded as a simple metric to assess the quality of exterior spaces such as the courtyards patios, parks, building entries, etc.

RESULTS

Site characteristics:

Figure 5 and Table 1 show typical error scenarios isolated for one hour. The location is a potential source for differences between an explicit interior Daysim simulation (reference case) and the new impulse response method. Latitude and longitude have an influence on the frequency of the occurrence of different sun angles. As expected, low sun angles and low radiation levels can be identified as sources of the deviation since the generalization requires sunlight to be diffused at the façade. Consequently, deep ray penetration cannot be modeled accurately. This leads to the error shown in Figure 5 in the center. The sunny morning shows a strong underestimation of the inner floor area. Another climate dependent source of error is the proportion of the diffuse and direct component of the light. Diffuser or “cloudier” climates yield smaller errors since the simplification to diffuse the light is “correct” more often. The diffuse sky condition depicted on the left, displays a small error with an underestimation of the near-façade area. The typical sunny day shows large deviations close to the facades. The correlation loses precision in high radiation ranges and tends to overestimate interior illuminance levels close to the facades. Table 2 shows how these three typical errors propagate into mean bias errors (MBE) and root mean square errors (RMSE) for an annual simulation with dynamic blinds in a sunny and cloudy climate. The deviation for DA and CDA are very small since it only matters whether the value is above or below the defined interior illuminance threshold.

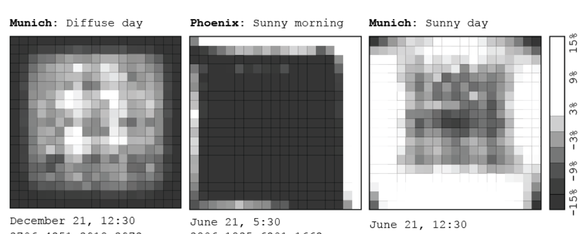

Figure 5 Mean bias error, location

Table 1: Measured error for three representative hours

Sky	Illuminace	DA	CDA
Diffuse	-7%MBE, 8 %RMSE	-9.3% MBE	-1.5% MBE
Low sun	-19%MBE, 27%RMSE	-11% MBE	-18.9% MBE
High sun	2%MBE, 5%RMSE	0% MBE	0% MBE

Table 2: Annual measured error for dynamic blinds

Loc.	Hourly Illuminace	DA	CDA
Munich	-6%MBE, 10%RMSE	-9.1%MBE	-4% MBE
Phoenix	-3%MBE, 13%RMSE	-11% MBE	-2.3% MBE

Table 3: Annual measured error of different shapes with constantly lowered diffusing blinds, Munich

Shape	Hourly Illuminace	CDA	DA
1	0%MBE, 8%RMSE	-0.6%MBE	-4.4%MBE
2	11%MBE, 13%RMSE	1.1%MBE	0.2%MBE
3	1%MBE, 7%RMSE	0.2%MBE	0.0%MBE
4	-3%MBE, 9%RMSE	0.0%MBE	0.0%MBE
5	-8%MBE, 14%RMSE	-1.1%MBE	0.0%MBE
WERK	-11% MBE, 13%RMSE	-3.8%MBE	-10%MBE

Table 4: Annual measured error of different shapes with constantly lowered diffusing blinds, Phoenix

Shape	Hourly Illuminace	CDA	DA
1	1%MBE, 10%RMSE	-0.5%MBE	0.0%MBE
2	12%MBE, 16%RMSE	0.2%MBE	0.0%MBE
3	2%MBE, 11%RMSE	-0.1%MBE	0.0%MBE
4	0%MBE, 13%RMSE	-0.1%MBE	0.0%MBE
5	-11%MBE, 18%RMSE	-0.8%MBE	0.0%MBE

Table 5: Simulation speed increase.

Simulation Scenario	Duration	Speedup
Dynamic blinds, 1 unit (case 1)(V1)	43 s	84 x
Static blinds, 5 units (case 2)(V1)	6 m	6 x
Real case, 244 units (case 3) (V1)	14 h	7.2 x
Real case, 244 units (case 3) (V2)	110 min	54.9 x

- *DA (Daylit area in sDA500lux/50%)*
- *CDA (Continuous daylight autonomy DA500lux)*

Geometry:

Table 3 and 4summarize the shape related errors. Shape 2 and 5 have the largest deviation from the Daysim results. The cross-shape(2), is largely affected by the error-proneness of the near-façade areas that was identified before. It shows a strong tendency of overestimation. The cut-off radius of the light propagation algorithm, assumes that façade segments that are further than 20m away from the interior sensor have no relevant influence. This leads to errors in extremely deep buildings. The fifth geometry shows an underestimation of the interior light levels due to this effect. This could be avoided by increasing the cut-off distance at the cost of a longer simulation time. Similarly to the previously shown cases the annual climate based metrics can be predicted with very high precision for all designs.

Case Study:

In the case study, it becomes noticeable that the sampling rate of the façade sensors is limited to one horizontal band with a sensor distance between 0.2m-1.0m. The highly irregular shading context cannot be modeled as detailed as the regular Daysim method and therefore leads to a slightly higher discrepancy in the results. However, this limitation still allows predicting the daylight metrics with a precision of 3.8 – 10%. The results are displayed in Table 3 under WERK. The graphical output of the results is demonstrated in Figure 6 and 7. Figure 6 gives a scene overview whereas Figure 7 can be used to analyze problem areas in detail. The parametric study (Figure 8) demonstrates the sensitivity of the two different metrics DA and CDA. The DA metric drops rapidly at a certain point since it is much stricter and only knows an on/off state compared to the CDA fraction. In addition the effect is enhanced because the altered window to wall ratio is modeled by a scaling factor that is applied to the incident solar radiation. This can be imagined as a frit that evenly covers the façade. This also explains why deviations in the interior illuminace predictions are pronounced much stronger in the DA than in the CDA metric. Figure 9 shows how the tool can be used to also evaluate outdoor spaces.

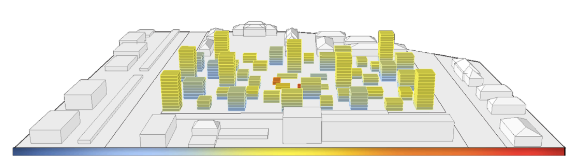

Figure 6. Unit daylit area sDA500/50%, WWR50% for massing iteration one.

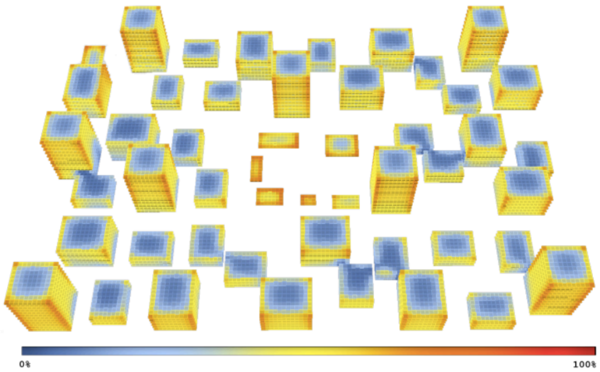

Figure 7. Node basedcDA500, WWR50% for massing iteration three.

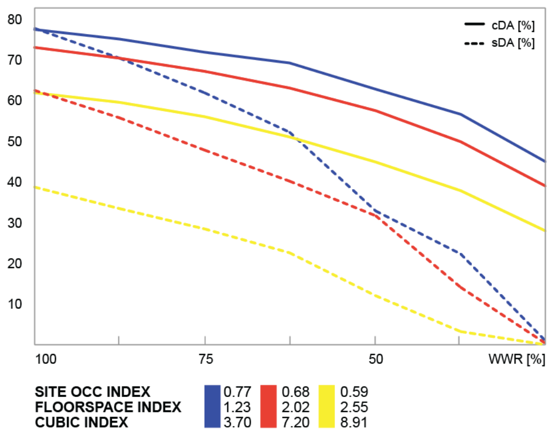

Figure 8. Parametric study showing three iterations with varying window to wall ratio.

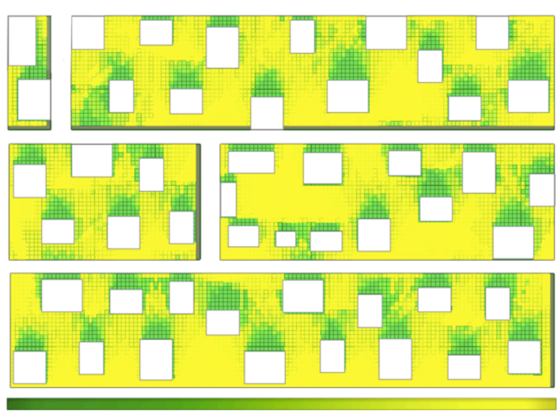

Figure9. Direct solar exposed hours for January to evaluate the quality of the outdoor space

DISCUSSION

Validity

The results have shown that the method yields reliable results for urban daylighting studies. The precision with a 7-18% RMSE for the interior hourly illuminance values is acceptable and within the bounds of the precision of the underlying simulation engine Daysim, which has an RMSE between 6-26% [Reinhart 2001]. The "Werkbundsiedlung" case study yields MBEs and RMSEs that correspond to the isolated cases. The daylight metrics CDA and DA prove to be less sensitive to the errors above since large portions of the illuminance value errors manifest themselves as overestimation in the near façade areas at high radiation levels. This error barely affects the final metrics since they both cap the values above the thresholds.

Required Effort

Simulation times for the "Werkbundsiedlung" are in the order of 60min for the exterior ray-trace and 50min for the interior light propagation. This is an increase in simulation speed of 54.9 times compared to the classic Daysim approach without dynamic blinds. Additionally, the fully automated workflow pushes large-scale simulations into a feasible realm.

For smaller scenarios with less than 10 separate units almost instant results can be achieved. This becomes interesting in combination with Grasshopper and its genetic algorithm "Galapagos". Then the method can be used as a powerful urban form giver.

A critical mind could argue that the development of a "faster" light propagation algorithm was a waste of time due to current developments in the computer realm. Similar to the "render-farms" known from the animation business, "cloud" services offer almost unlimited processor power for an affordable price. In addition, speed optimization of Radiance could make the developed algorithm obsolete.

However, the authors believe that splitting up the process into an interior and exterior light propagation calculation has more benefits than just the speed advantage. The method yields several useful intermediate results, such as radiation on the façade, that are of similar interest to the designer as the interior daylight autonomy. It is inevitable that the solar exposure on the facades and the daylight autonomy need to be developed together, seeking mutual resolution of the sometimes conflicting demands. Further processing of this data with Energy Plus to predict the energy use intensity of the building has been tested and is under development. This would then also allow predicting undesirable over-heating and could demonstrate, in greater detail, the potential of passive solar heating.

Another benefit is the ease to simulate dynamic blind systems. For a space with just four different facades, Daysim needs to simulate 14 different conditions and then "mix" the results. Here the new method is 84 times faster in addition to the much easier model setup.

Future improvements

For the future it is important to further remove the geometric limitations. Skylights or punched window facades can only be modeled indirectly. The Authors plan to integrate a radiosity-based algorithm to remove these limitations. This would also allow taking direct sunlight penetration into account and could improve the overall precision of the tool.

A common disadvantage of many evaluation tools and the accompanying metrics is that it is often hard to judge and rank the computed results. Only through experience and through looking at multiple design variants iteratively we can say if a result is "good" or "bad". The authors plan to mitigate this inconvenience by generating a database that can be derived from a broad study of urban typologies, densities and their daylight performance. This could then be included in the tool as a "guide" system that can give feedback how good a result is compared to the known optimum.

CONCLUSION

The novel approach to calculate exterior radiation distribution paired with the generalized light propagation algorithm to compute the interior illumination distribution, introduces a method that is 54.9 to 84 times faster than the standard Daysim/Radiance approach. Additionally, the model setup is fully automated. For the first time, it becomes possible to evaluate the daylight potential of urban designs within a feasible amount of time. The hourly results and the satisfactory precision of 7-18% for the interior illuminace and 3.8 – 10% for the climate based metrics allow us to study urban designs in great detail easily.

ACKNOWLEDGMENT

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