INTERACTIVE SOLAR POTENTIAL SIMULATION FOR EARLY STAGE URBAN PLANNING

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ABSTRACT

The early design stages of urban planning have a great impact on indoor comfort and energy aspects. Alternative power supply options, based on solar potential, should be considered in the early stages of design, as they may constitute highly efficient substitutes. Existing software solutions for such simulations require higher level of detail from models, precise input parameters and have long, non-interactive simulation runtimes. This is in stark contrast to the rapid changes that happen to the imprecise models used in early design stages. The focus of the paper is the core concept, theoretical approach and the prototypical implementation of a real-time, interactive algorithm focused on solar potential for buildings.

INTRODUCTION

The effects of decisions taken in the early design stages have significant effects not only on the subsequent planning phases, but also on construction operations and the use of the building (MacLeamy, 2004). It is therefore even more essential to be able to assess these effects at an early stage of planning, particularly in the field of energy planning. However, energy estimates take place in the later phases through analyses and simulations that require highly accurate models and data – information that is not available in early planning phases. It is therefore necessary to find approaches and solutions that enable an estimation of energy factors based on imprecise, incomplete data and at the same time allow embedding in early planning phases.

CDP // Collaborative Design Platform

In recent years, a research group has investigated the seamlessly embedding of simulation and analysis tools in the early planning and design phases. In addition to the definition of relevant requirements for design tools. The conceptual basis of the existing CDP // Collaborative Design Platform (Schubert, 2014) bridges the gap between the digital decision supporting tools and stablished design tools in the creative planning phases. This allows participants to work with familiar tools and simultaneously display analyses and simulations directly in the model or hand-drawn sketches that extend the scope of assessment by additional digital levels.

The system structure can be shown as follows: The hardware is based on a large-format multi-touch table built in-house (Figure 1). The table surface serves (Figure 1 A) as a work surface and shows the digital image of the figure ground plan. Additionally an on-top depth camera allows for real-time reconstruction of all physical objects placed on the table. In this way, all design ideas are also directly available as digital data in the form of models. This data serves as the basis for the simulations and analyses displayed on the table surface. Due to the real-time connection, a change in the object has a direct effect on the simulations, so that the effects are directly visible. To enable the creation of different analysis tools a plugin framework was integrated into the CDP (Figure 2) to allow for a standardized handling of user interactions and events and enable an easy way to visualize the results of simulation and analysis methods in the CDP framework.

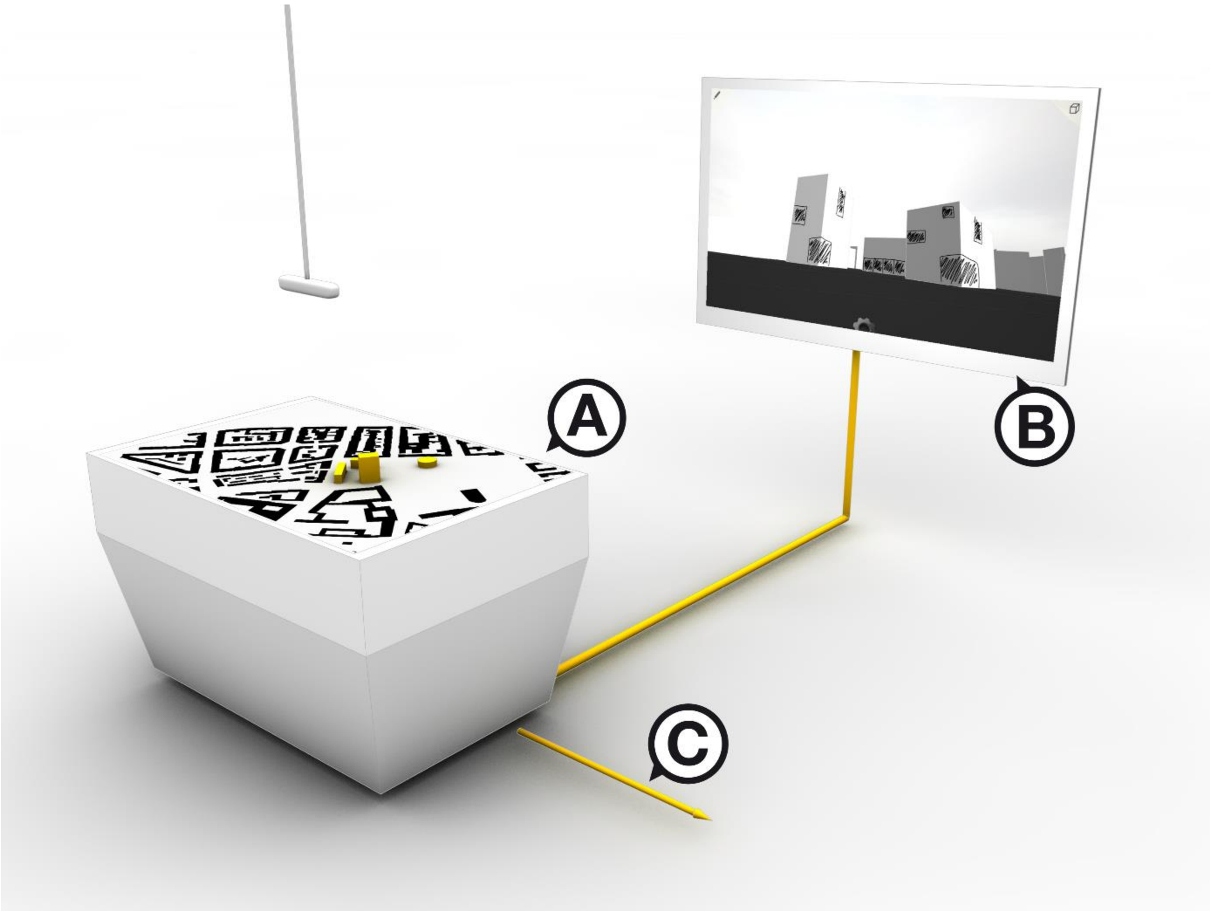

Figure 1: Hardware Setup of the design platform: A) Table Surface; B) 3D Perspective View; C) Flexible Extensions

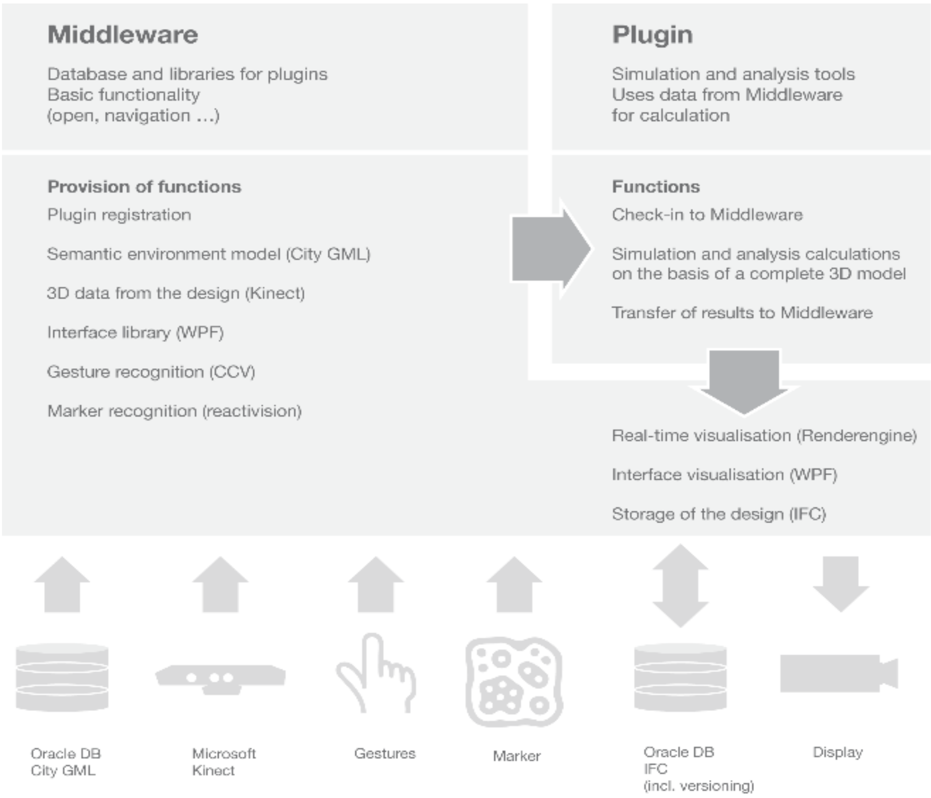

Figure 2: Software Framework of the design platform: the simulation is built as a plugin

CONCEPT

Taking into consideration the described design platform, this paper proposes a method and prototypical implementation of an energy analyses simulation focused on the solar potential of individual buildings in an urban environment in real-time.

Related Works

For the purposes of the research project, a few tools and approaches for analyzing the solar potential of buildings were selected and observed.

The RADIANCE (Ward, 1994) software serves as a core for many popular commercial plug-ins and tools. It utilizes a backwards raytracing algorithm that considers both diffuse and specular reflections. It is an ideal base for complex detailed models, where precise results are essential. Due to its freeware nature it is widely utilized in applications related to solar potential estimates and daylighting analysis.

As an improvement to the preexisting ESRA clear-sky model (Hofierka, 1997), r.sun (Hofierka et al, 2002) enables calculations to be performed for large areas. Reflectance and shadow maps are produced for the different types of surfaces through the discretization of different input parameters such as terrain, latitude, and radiation irradiance and irradiation raster. The model support of different time steps and intervals.

A widely popular software solution for radiation models is the Solar Analyst (Fu et al, 1999), developed for ArcView GIS (ESRI 1999) as an extension. The method divides the sky into different sectors defined by the zenith and azimuth coordinates. It computes a set of radiation maps based on a uniform or standard overcast sky.

All of these software solutions share a few similar drawbacks when it comes down to their integration in the early stages of urban planning. The algorithms used deliver high precision result for detailed models. Applying them to the lower level of detail models that are used in the early design stages would be highly impractical. Another issue related to their highly precise computation potential is, that they require non-interactive computational times and are not geared towards handling changes to the simulation models during the process.

Theory

The goal of the proposed approach is to compute the energy potential of optimally place photovoltaic solar panels and how that would relate to the energy requirements of the building itself.

The computation of the total radiation flux is based on the approach proposed by (Holbert 2011). It is the sum of the direct radiation flux:

$$\mathrm{I_D} = \mathrm{I_{DN}} cos(\theta) \tag{1}$$

the diffuse-scattered radiation flux:

$$I_{DS} = C\, I_{DN} \left[\frac{1+\cos(\beta_2)}{2}\right] \tag{2}$$

and the reflected radiation flux:

$$\mathrm{I}_{DR} = \mathrm{I_{DN}}\rho(C+\sin(\beta_1)) \left[\frac{1-\cos(\beta_2)}{2}\right] \tag{3}$$

where I_{DN} is the direct normal irradiance to the ground, θ is the collector angle, β_1 is the altitude angle and β_2 is the tilt angle from the ground. A,B and C are the apparent solar irradiation, atmospheric extinction coefficient and the ratio of diffused radiation on a horizontal surface to the direct normal irradiation respectfully. (ASHRAE 1995)

Roofs facing north, northwest and northeast (azimuth of +135° to -135°) were excluded due to the low solar radiation and the correspondingly low efficiency and economy of power generation. If no roof information is provided (type, orientation, inclination, etc.) it is assumed that it is a flat roof.

The amount of electricity that can be generated per year per roof area of each individual building was determined using an average annual efficiency factor. For a better interpretation of the results, this value was shown in relation to the power requirements of the respective building. Since the real electricity consumption of the building is not known in principle, the demand was estimated based on statistical area-specific values (Frondel et al., 2008).

IMPLEMENTATION

The most computationally intensive part of the proposed approach is the assertion if parts of the roof are occluded by other buildings and objects. That is why the algorithm consists of a two-step approach: Step 1 computes a fast, optimal situation. Step 2 improves iteratively the result.

The two-step approach can be divided in 3 general phases (Figure 3). These 3 phases are then divided into three background threads. The „preprocessing" phase computes the static building data that does not change over the course of the simulation. The "fast" phase computes an idealized real-time result. In the "accurate" phase, the idealized result is improved, by taking into consideration shadow occlusion.

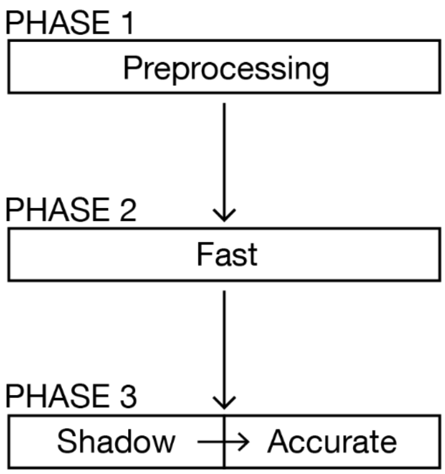

Figure 3: The three main phases of the algorithm

Phase 1: Preprocessing

As a first step in the preprocessing phase, the plan area is roughly discretized based on latitude and longitude coordinates. This is done since the difference of the solar altitude and azimuth angle between two points that are only a few meters apart is negligible. Then for each of the discretize coordinates the sun elevation and direction, and the solar azimuth are computed and stored for each time step in which the sun would have been visible.

In the preprocessing phase, three major operations happen per building. The first is the computation of the estimated electricity consumption of buildings. Based on the contained data in the OpenStreet Map model the energy reference area (erf) is obtained. This is either the total living/usable area or as:

$$erf = l * area * scale\_factor \qquad (4)$$

where l is the number of floors, not counting the basement, the $area$ is the building floor area and the $scale\_factor$ is a value in the range $[0,1]$ that defines how much of the floor area is actually usable. After the energy reference area is computed it is multiplied with a statistical energy value, based on the type of building and its age. This type of data can either be directly read from a file or preloaded into the simulation.

In parallel, the buildings are subdivided into convex parts using the Hertel-Mehlhorn algorithm (Hertel et al, 1983). This is done to simplify the shadow generation and the occlusion tests in the next steps.

After the segmentation, the roof of the building is discretized for the purpose of shadow computations. A 2D Bounding Box (O'Rourke 1985) is generated for the roof, and then it is discretized with a Cartesian grid. Each cell that does not consists of more than 50% roof is then removed from the list. The cells themselves contain only a position in 3D Space and its corresponding approximation in latitude and longitude coordinates.

Phase 2: Fast Thread

The goal of the fast thread is to deliver an instant result that can then be improved gradually. The thread performs an idealized scenario for each roof, meaning that it is not occluded by anything. The ideal potential is computed as:

$$potential = tsrf * sp * psf \qquad (5)$$

where $tsrf$ is the solar radiation flux, psf is the annual efficiency factor for photovoltaic panels (STMUG 2011) and sp is the total amount of solar panels, that could be optimally placed on the roof.

The solar panel count is computed based on the total roof surface area scaled by a factor for unusable space (skylights, dormers, chimneys, air conditioning, etc.)(Müller 2009) and a second factor that represents optimal positioning of the solar panels on a flat roof (STMUG 2011). For non-flat roofs, the orientation and the inclination of the roof are taken into consideration for the optimal positioning factor. This computation is then split per building per time interval as a singular function and executed in parallel. Each result for each time interval for each building is then stored, so it can be improved by the second pass of the algorithm. Since this thread performs only computations that are done in constant time, results can be visualized for the user in real time.

Phase 3: Accurate Threads

Once the thread is complete, the second phase begins. There are two processes that run in parallel one generates the shadows for each building for each time interval. The second one uses the results of the first to compute a realistic potential for the building by expanding on Eq. (5) by adding an occluded factor that represents how much of the roof would be in shadow for that time interval.

The test, if a point is occluded by another object can be reduced from a three dimensional problem to a two dimensional problem, since the bases of all objects are on the same plane (topology of the area is not taken into consideration). By projecting the 3D object to a plane, the occlusion test can be reduced to checking if a point is inside of a polygon. The projection vector is the sun direction for the specific time interval. This test is further simplified, since all buildings are split into convex shapes only. This means that the projection of the convex 3D parts is then in turn also a convex polygon (Martin et al, 2002).

As a further optimization for the occlusion test, each shadow for each time interval also has a 3D Bounding Box generated. The minimum and maximum points of this box are computed using the points of the building volume and the projected 2D shadow polygon (Figure 4). A check is then executed to identify if a point is within a box in constant time and is used as a fast way to skip occlusion tests for shadows and buildings that are far away. A final bounding box for each building is constantly updated during the shadow computation thread. Its points are computed using the building volume points and the complete shadowing area, produced by all of the shadows from each time interval. This bounding box represents the total area that is shadowed by the building through the whole time span (Figure 4).

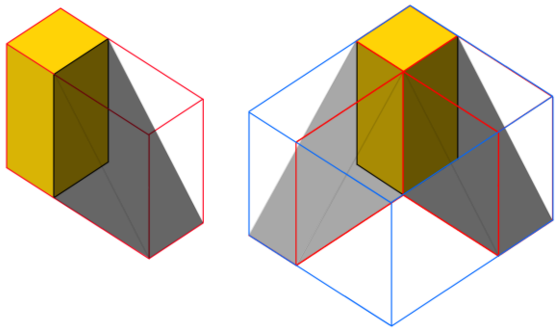

Figure 4: Bounding Box for a single shadow (red, left); Bounding Box for all shadows (blue, right)

When the shadows for each building for one time step are computed, the second process does the occlusion test. Since the roofs were already discretized in a previous step, it projects the center point of each cell to the ground plane, using the same sun direction vector as the projection vector, and then tests if the point is contained within one of the shadow polygons. Once each cell for the roof has been tested, the occluded proportion is used as the occluding factor for (5) and the previously stored result is then updated.

Real-time Interactivity

To have a simulation that reacts to the changes of the planed area made by the user three cases have to be handled: when a new building is placed, a building is moved or rotated and when a building is removed. What happens in all three cases as a first step is a stop of all running threads. Once the threads are terminated, the different cases are then handled. As an optimization for this part the buildings where extended with three variables that track how much work has been already done by the three threads. Once the threads are started, they execute their methods only on the buildings that are marked for update.

When a new building is added to the plan area, it starts the optimal simulation thread to deliver an instant approximation for the solar potential of the building. The shadow creation thread is then executed exclusively for the new building. Since the new building will produce shadows that will affect the solar potential of other neighboring buildings, all other buildings have to be checked if they would be shadowed by the new addition. For this purpose a fast Bounding Box overlapping test between the complete shadowing Bounding Box of the new building and the Bounding Box of the roofs of each other building is performed. The corresponding buildings that will be affected by the new addition are then marked for solar potential recomputation. The threads are then started again with the updated tracking variables.

Similarly, when a building is removed, the solar potential of neighboring buildings would improve. Using the same overlapping tests as with the case of a new building being added, affected buildings are marked. Then the information about the removed building is deleted from the lists and the threads are restarted.

The most complex case is the movement of a building in the plan area. The movement of a building consist of two events. First the neighboring buildings around the original position of the building would have a solar potential gain, since there will be one less occludes. Second, the neighboring buildings around the new position of the building would have a solar potential loss. The overlapping test is first used in the original position of the building using the complete shadowing Bounding Box and roof Bounding Boxes of all buildings. The affected buildings are marked and then the building is moved and its new shadows are recomputed using the shadow creation thread. After that, the same overlapping test is performed between the new complete shadowing Bounding Box and all roof Bounding Boxes. After the affected buildings are marked, the threads are restarted.

Figure 5: Representation of the percentage of electricity consumption that can be covered by solar energy; buildings marked in red are excluded from the analysis.

VALIDATION

To validate the implementation of the proposed approach an area in the vicinity of Munich was selected. The time interval is one year with steps for each hour. Due to the low level of roof information in that area, all roofs were set to the flat roof type and the solar panels to have a 35° degree inclination. The values of the simulation were then extracted and compared with the results of the corresponding radiation values calculated with the ASHRAE tool and Radiance.

The first tool used for validation “ASHRAE Clear Day Model Solar Calculator” was developed by the University of Minnesota based on calculations by (Kuen et al, 1998). This model also uses location-based data (latitude and longitude) without consideration of weather data and exclusively for a clear sky. For the validation, hourly direct and diffuse solar radiation values were calculated to determine the monthly solar potential. Figure 6 show the linear regression for the annual solar radiation in comparison between the implemented simulation and the ASHRAE tool. The detailed analysis of the results yields a determination coefficient factor of 0.97 to 0.99, which confirms the high accuracy of the implemented method compared to the ASHRAE tool.

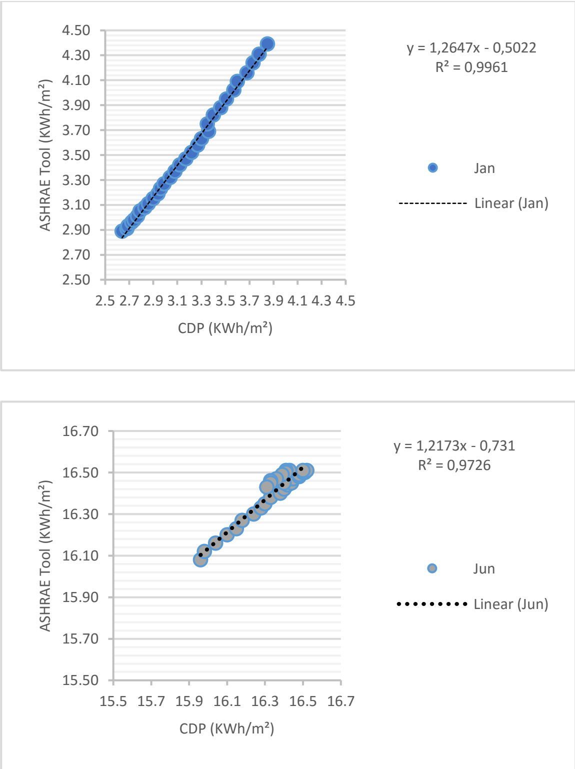

Figure 6: Monthly global solar Radiation (January, July)

The second tool used for the validation is Radiance, which takes weather data for the plan area under consideration including direct and diffused horizontal radiation and clouds. The tool provided significantly lower values for the solar irradiation (Figure 7). One of the main reasons for this drastic difference between the results from the implemented simulation and the radiance simulation is the high cloud coverage around the Munich plan area, derived from the local weather data.

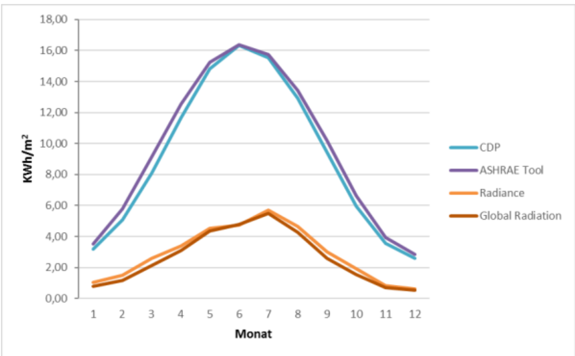

Figure 7: Monthly comparison of solar radiation values for the city of Munich

CONCLUSTION / FUTURE WORK

The implemented simulation for calculating the solar energy potential is intended for comparative studies in the early stages of urban planning in order to compare and evaluate corresponding design variants. The proven overestimation of the solar potential due to the exclusion of local weather data can be neglected as long as the results serve exclusively for the comparison of variants.

A future improvement on the implemented approach is to include the aforementioned weather data into the mathematical model of the simulation.

For the improvement of the occlusion tests, the planning area can be subdivided using different type of spatial partition strategies. This could greatly improve the computation time for the different cases in real-time interactivity of the implementation.

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