**ABSTRACT**

This paper presents a tool that enhances the comparison between daylight-based heatmaps of different architectural solutions. While the literature debates extensively on methods to represent annual daylight simulation data there is no serious effort to develop a tool that supports decision making processes based on iteration of different design variations in daylight performance based design. This work discuss the visualization approaches used in the field of architectural daylight assessment, their limitations and advantages in order to structure an effective method that supports comparison between different instantiations or solutions for the same design problem. The proposed tool is based in linking and brushing different graphical representations of data from daylight building simulations that will deepen the understanding of the performance of each solution. Finally, the proposed method can be extended to other domains or problems which data visualizations are based on heatmaps.

**Author Keywords**

Daylight simulation-based design; visualization of building simulations; JavaScript; D3; heatmaps, brushing and linking.

**INTRODUCTION**

"Architecture is the learned game, correct and magnificent, of forms assembled in the light." [1]

Computer graphics had been a great impact in the architectural design field. Three-modelling and visualization software, Computer Aided Design (CAD), and physical-based simulation engines (e.g. Finite Element Methods software based tools, whole-energy simulation package such as EnergyPlus [2], etc.) had changed the way architects work and assess their designs. Digital simulation tools have been particularly important as a medium to inform and steer design processes from early to final stages. These simulation tools models the physical behavior of buildings under different criteria that can be clustered in two main groups: structural behavior, and environmental performance. On the side of environmental performance two main types of simulations are typically: daylighting and energy/thermal simulations. The data generated by these simulations can support decision making processes namely through a set of standard visualizations presented to the designer. Those visualizations intend to support the designer in design assessment actions that will be the basis to accept a design solution in prejudice of another, or to remodel and reassess building performance in an iterative loop until the desired design criteria is met.

Light and shadow are ever present qualities in architecture like figure and ground are on the visual arts. Like Le Corbusier so well stated, architecture only fully emerges when exposed to light. That is why quantitative and qualitative daylight assessment is one of the most used methods by architects to test and explore the space solution of a particular design problem. Therefore, this work will address data visualization that results from quantitative daylight simulations. The data produced from this type of simulation are particularly interesting because they address simultaneous value, time and spatial attributes/qualities (e.g. position, transition of value through space, differences between light attributes in the building envelope, etc.). Although the ability to address and visualize yearly based simulations has been already addressed in the past, either by the creation and adoption of new daylight metrics (e.g. Useful Daylight Illuminance - UDI - or Daylight Autonomy - DA) [3] or by visualization tools that resorts to interactive zoom techniques [4], there is no tool that automatically parse and support the visual comparison the data from quantitative daylight simulations of different design solutions.

Architectural design is based in a series of iterative explorations where different instantiations of the same design are tested against each other under different criteria (e.g. aesthetics, functionality, economic, energy consumption, daylight performance). The design evolves trough this discrete steps of selection (see Figure 1) [5]. The inherent spatial resolution of daylight simulation data proposes a challenge to question traditional bi-dimensional static visualizations and an opportunity to assess how a set of interactive transitions can improve the exploration and reasoning about the daylight performance of different instantiations of the same architectural design. Thus, this work proposes a method that will help architects and other designers or specialists in decision processes that involve daylight quantitative simulations.
RELATED WORK

Regarding daylight digital simulations, Radiance [6] is the reference software. Radiance was created in the Lawrence Berkeley National Laboratory (LBNL) and it is composed by a suit of programs dedicated to architectural visualization and light studies, through either physically accurate renders or false-color images. Based on ray tracing algorithms, Radiance is a research based tool that can be used directly through a terminal or through a Graphical User Interface (GUI) that usually interacts with a CAD software. Recent development of GUI’s for Radiance enable architects, interior designers and light engineers to interact more easily with it from a popular 3D NURBS (Non-Uniform Ratio Basis Splines) CAD software, Rhinoceros 3D [7]. Some of these interfaces, such as DIVA [8, 9] and Honeybee [10], allow designers to combine fully parameterized building models with daylight simulations through the Visual Programming Language, Grasshopper. The typical workflow of a daylight simulation through these GUIs can be resumed in the follow steps:

- Definition of scene geometry;
- Assign materials to the geometry;
- Sky model definition;
- Defining the Photo-sensor (the sensor that will read the desired daylight metric value) grid, also known as workplane (see Figure 2), or camera perspective;
- Select type of simulation (render, point-in-time or annual-based metrics);
- Run the simulation;
- Parse and Visualize/Read the simulation results.

The standard visualizations of Radiance simulations are Heatmaps, contour plots, false-color images and renders. Renders and false color image is an attempt to correlate qualitative and quantitative data and they will not be addressed in this work due their inherent subjectivity, and the difficulty to translate qualitative design criteria to a measurable metric (such as aesthetics). Although this work only addresses the inherent problems to quantitative daylight analysis it is worthy to mention that current research has been done in the front of assessing daylight spatial quality with quantitative metrics [11].

Regarding quantitative metrics they can be group in two general groups: point-in-time simulations, and annual simulations. Initially, Radiance only allowed architects to perform point-in-time simulations, such as illuminance calculations. This means that a single simulation refers to a specific hour of a specific day of the year. Annual daylight simulations were introduced in Radiance framework by the Three-phased Method process (which include recent functions to the Radiance package, such as detimestep) [12], or the more user-friendly Daysim add-on [13]. Annual simulations expand point-in-time illuminance evaluation to the 8760 hours of the year. This means that for each Photo-sensor it will be recorded an array that will contain 8760 illuminance values, each one per each hour of the year. Because these simulations introduce another dimension to the data, time, different metrics were created with the objective to bin/synthesize the considerable amount of data created by the simulation. Annual-based daylight metrics resumes the annual data compiled in each photosensor to one value: percentage of time that each node is above, below or within a specific illuminance value or range defined by the user or by the metric itself. One of the most common used annual-based metrics are Daylight Autonomy (DA), which measures the percentage of time that a specific node is above or equal an illuminance threshold defined by the user, and Useful Daylight Illuminance (UDI), which bin
the percentage of time for each node below 100 lux, between 100-2000 lux, and above 2000 lux. The creation of this metrics aimed to summarize in a measurable and meaningful list of single values that can easily be mapped in a heatmap or contour plot. In this way the value encodes time while the graphical representation as spatial position embedded. However, in the transformation of annual data recorded in each sensor to a single value there is always information loss and sometimes it is important to convey the illuminance trend over time. The way that annual-daylight metrics are build is by parsing and manipulating a text file produce by annual simulations calculated with Daysim, and/or Radiance, the *.ill file (the ill extension refers directly to illuminance). Is in this file that the arrays of illuminance values of each hour of the year per photosensor are stored.

Past and current research tools approach different ways to represent the entire data-set of *.ill files. Glaser and Ubbelohde [14] propose the tessellation of illuminance calendars (also called temporal maps) for each photosensor. Each temporal map is a heatmap that encodes value in color over time, where the x-axis represent days while y-axis hours of the day (see Figure 3). Brushing and linking allows further visual exploration of the annual illuminance data-set. Due to resolution and the limited space of the canvas this technique has problems in sampling the calendar view for each sensor. Also, although this method can convey value in space over time in a single representation, it is hard to make an overall assessment from the resulting visualization.

Kleindienst et al [15] proposes pairing temporal maps, of the values recorded in a single photosensor, with a single point-in-time set of renders of different design solutions. By resorting to renders this technique helps the designers to assess qualitatively how light performs in different solutions. The temporal heatmaps inform the designer how solutions are performing through time (see Figure 4). This technique has some limitations: it is hard to determine the sampling of point-in-time renders for the comparison; for solutions with similar performance is difficult to assess which is the best in both, renders and heatmaps; the temporal heatmaps do not show how light propagates and decays in space, thus lacking the spatial resolution which is fundamental in architectural daylight studies, and finally comparing areas and colors are not the best functions of human perception.

Space Series [4] is a tool that resorts to brushing, linking, and interactive zooming techniques and fully addresses the problem of visualize annual-based daylight simulations with illuminance heatmaps. This tool proposes an initial temporal map where for each hour of the year the average illuminance of the photosensor grid is computed (see Figure 5).

Figure 3. Sampled annual-illuminance from the annual daylight simulation in a calendar view per sensor. Source: [14]

Figure 4. The dashboard proposed by Kleindest et al [15] for compare daylight performance of different design solutions. Source: [15].

Figure 5. Space Series’ initial temporal map. Each pixel corresponds to an illuminance average of the photosensor grid for a specific day and hour. Like every temporal maps of this kind, the horizontal axis measures days while the vertical axis is measures hours of a day. Source: [4].

The user can interactively navigate this initial averaged heatmap and expand it through zooming the context (C)
both in the horizontal axis (days of the year) – the day focus ($F_d$) - and in the vertical one (hours of the day) – the fractional hour focus ($F_h$) (see Figure 6). In the intersection of these two zooms a subset presents the entire data for each constant point-in-time in the subset of days and hours (see Figure 7).

![Figure 6. An example layout in Space Series consisting of C, Fd, Fh, and F2 regions. Smaller rectangles within regions outline temporally distinct data. F2 regions present data at a constant point in time. Source: [4].](image)

In the initial average graph the user can identify particular points of interest and then further explore them with the zoom capabilities of Space Series. By zooming a subset the total illuminance data is displayed. Thus in a single dashboard all the data present in a *.ill file can be visualized interactively.

**PROBLEM**

In the related work we could observe that the topic of annual illuminance data of a photosensor grid visualization has been seriously address and solved either by different daylight metrics, such as DA or UDI, or by interactive visualization tools based on zooming [4]. The comparison between different design solutions was only slightly approached in the dashboard proposed by Kleindienst et al [15] which automates pairing layouts of heatmaps and renders, a technique that is currently done by daylight expert but manually. Plus, by focusing the temporal maps in a single photosensor this dashboard is not able to express accurately how light behaves/decays in space. On the other hand Space Series, although it deals with the time dimension exceptionally, it does not support effective comparison of different design scenarios, because the tool is only ready to parse the data of a single annual-daylight simulation and all comparison tasks are visual and done directly by the user.

All the tools base their visualization of daylight simulations in heatmaps, namely because they are effective in convey space or time, and value. Heatmaps are also good in express overall performance or trends in the data-set to which they refer, but they pose some difficulties in detailed reading and in comparison tasks, namely due to human perception limitations in comparing areas and colors. That is why some daylight experts complement their studies with different types of visualization for a more detailed analysis, such as line or bar graphs. A line-graph in daylight studies normally represent how light decays in section. In the x-axis the photosensors, which are in a specific section of the workplane, are marked, and in the y-axis is measured their correspondent illuminance values. Although very accurate and precise, line-graphs are only able to show partial data. When this type of graph is used to understand the light distribution of an entire space, by overlaying all possible daylight sections, the spatial structure and correspondent light performance becomes very difficult to understand. Figure 8 shows how the line graph becomes cluttered and needs extensive annotation marks to be readable.

![Figure 8. Juxtaposition of 11 Daylight Factor curves in a line chart. Daylight Factor is a ratio between exterior and interior illuminance under an overcasted sky.](image)
By encoding value in color hue, the Heatmap is extremely dependent from the scale of the color range. Outliers, which fall off the range, are not typically shown. One might think that a simple update to the color scale could solve the problem, but that update most of the times result in a loss of granularity, making the heatmap difficult to read by the lost of its natural gradation pattern. On the other hand, other type of graphs, such as boxplots, can effectively show outliers. More, they can easily synthesize the distribution of values in quartiles, conveying in a very simple way how a specific solution is performing. Although boxplots are easy to compare, they are unable to encode both spatial features and value.

We can concluded that in design comparison tasks based on daylight performance is not only desirable to compare spatial patterns and trends through heatmaps but also to compare more detailed levels of the data that normally are easily visualized with other type of charts, such as line charts, histograms, and boxplots. Thus, instead of focusing in the improvement or creation of a single type of visualization, the comparing the daylight performance of different design solutions can benefit by linking the already used graph types in the domain to inform better decision processes in architecture. Although this problem is domain-oriented it can be extended to other domains where heatmaps are fundamental. In matter of fact, by focusing on the problem of building daylight simulation visualization we are simultaneous addressing two different problems which are, nevertheless, interconnected:

- Daylight architectural studies: How to expand the meaning of daylight simulations through visualizations? How data can be displayed to inform more effectively the design process?
- Problems of the domain of data visualization, namely: How should we enhance/improve Heatmaps visualizations? How do we solve the problem of heatmaps comparison?

ENVISIONED SOLUTION - DAYLIGHT COMPARISON TOOL
In order to address the problem of comparing several design solutions under the scope of daylight performance, an interactive dashboard is proposed. This dashboard links synchronously different views of the data to better inform the designer or daylight analyst and support their decisions or recommendations. In order to further explain the proposed solution the following subsections will address: goal and scope, approach and results.

Goal and scope
The main goal of this work is to develop a tool that can support designers in daylight-based design processes where different alternatives or design instantiations need to be compared. Because daylight design is based mostly in heatmaps this work can be extended for different analysis processes that rely on heatmap data visualizations. Because different graph types are “traditionally” used in the field of performance-based architectural design, this work aims to explore several types of interaction, such as brushing and linking procedures, to enhance sense-making from data visualizations based on heatmaps. Finally, and because this work only target the comparison of different solutions, annual-based daylight simulations will not be addressed. The purpose of this work is to build upon existing tools that are able to parse and visual encode time and space in a single graphic, such as Space Series. Therefore, the Daylight Comparison Tool should be understood as an extension of the capabilities of existing tools that already deal with the problem of annual-based daylight simulations.

In summary, linking different types of graphical representations of the same data allows the user to perform a visual, spatial, and quantitative comparison for a more complete and informed analysis. The power of analysis is augmented by coupling this system with others that promote a fluid and effective navigation in annual-based daylight simulations. With better analysis techniques the designer can make better assumptions and decisions (see Figure 9).

![Figure 9. Conceptual goals for the Daylight Comparison Tool: outlined in gray is an example of a tool that can be extended.](image)

**Approach**
The approach set for this work is two-folded. The first approach refers to the layout of the proposed dashboard. The second is related with interactivity techniques such as brushing and linking.

Regarding the structure of the tool, a dashboard is proposed. The dashboard paradigm is suitable to a tool that is based on different representations of the same data-set. The layout of this dashboard consists in the splitting of a canvas in two areas: the upper canvas and the lower canvas. The upper canvas is dedicated to visualizations that relate the data with its spatial position. There we can find three heatmaps: Solution A, Solution B and the Delta heatmap, which is a computation of the difference between Solution A and Solution B. Solution A and Solution B have a synchronized color scale in order to facilitate visual comparison tasks. The Delta Heatmap shows where Solution A has higher or lower performance than Solution B. At the right part of the upper canvas we find a slider...
which the user can use to query the data of Solution A and Solution B.

The lower canvas is dedicated only to quantitative graph types and is divided in two parts. On the left we find two histograms, one per solution. Each of them shows the illuminance distribution by the counts of nodes that fall in a specific illuminance bin. The right part of the lower canvas is reserved for the summary graphs, two boxplots (one per solution) that synthesizes the daylight performance of each solution. Figure 10 shows the final layout of the Daylight Comparison tool.

![Daylight Comparison Tool dashboard](image)

**Figure 10. Daylight Comparison Tool dashboard running in Google Chrome web browser.**

The approach followed for interactivity is based in how user brushing triggers synchronized bidirectional interactions among the visualizations on the dashboard. This means when the user selects or hover something in a graph something will be updated or highlighted in the others. The different types of interaction are:

A. Heatmap Cell, Row or Column selection → Update Boxplot and Histogram: this allows the daylight analyst to conduct section base analysis, this is to observe how light decays along the length or the width of the room. Because we are dealing with comparisons, the cell, row or column selection are synched between the three heatmaps. The Delta map is a static map but the selection area is still present serving as a visual helper that highlights the photosensors under study.

B. Heatmap Area selection → Update Boxplot and Histogram: it is a generalization of the Type A interaction. This interaction allows designers to conduct comparison in a selected area of the room.

C. Filtering by value → Hide heatmap cells: because daylight performance of buildings also needs to meet building standards and codes, that impose some thresholds to illuminance values, or optimal illuminance for certain activities, a slider was provided to the user that will hide the cells of the heatmap cells that are below a certain illuminance value. This helps the designer to observe if quantitative data displays (the graphs in the lower canvas) are not being distorted by outliers and also if the solution is going towards code/standards and/or functional daylight criteria.

D. Hover on Boxplot or in Histogram → Highlight heatmap cells: because the boxplot quickly synthesizes the daylight performance of each solution it is useful to the user indentify where are the nodes that belongs to the different quartiles. This is more important in the design of complex fenestration systems that distributes daylight in non-usual patterns.

Finally the dashboard and interactions were implemented in JavaScript resorting to the D3 library [16]. This allows to run the tool in web browsers which facilitates, widespread and promotes its using.

**Results**

Figures 11, 12, 13, 14 and 15 illustrate how a designer or a daylight analyst can use the Daylight Comparison Tool and its functionalities. All the spectrum of interactions types are represented in the Figures.

Figure 11 shows an example of the tool behavior when the user selects a column in a single heatmap. This is a Type A interaction. We can observe that the selection window is updated in the other heatmaps and that the histogram and boxplot only refers to the selection that is been made. We can observe that the window selection also show and updated in the static Delta map helps the user to read where and how much Solution A has higher and lower illuminance than Solution B.

![Daylight Comparison Tool](image)

**Figure 11. Heatmap row or column window selection.**
Figure 12. Heatmap area selection.
Figure 12 shows a Type B interaction. The user drags a window in one of the heatmaps and the correspondent area selection in the other heatmaps, histograms and boxplots are updated. The features of this action are similar to the features presented in Figure 11.

Figure 13. Filtering by value.
Figure 13 exemplifies a Type C interaction. The value on the filter slider was updated to 300 lux. The cells on Solution A and B heatmaps that were below the slider threshold were occluded. This allows the user to evaluate where and how each solution is meeting a certain illuminance criteria. Because the delta map is a computed map between Solution A and B this slider does not have an impact on it.

Figure 14 shows a Type D interaction. While mouse hovering a specific bar of a histogram the correspondent heatmap cells are highlighted. In this case a bar around 600 lux in solution A was mouse hovered. The correspondent cells on Solution A heatmap are highlighted with a brighter color considering the context. Figure 15 demonstrates other Type D interaction, hovering the boxplot. In this case we can observe the upper first quartile being highlighted with a brighter color in Solution A heatmap.

Figure 15. Boxplot mouse hover.

By providing simultaneous different views of the same data in a single dashboard, and enhance it with brushing and linking interactions, data and sense-making tasks can become easier and contribute to the quality in the decision between different design alternatives. This dashboard also promotes data exploratory tasks that otherwise would be time consuming or probably not even made at all.

FUTURE WORK
The Daylight Comparison Tool is still a prototype that, first of all, makes a proof of concept. Therefore, some improvements need to be conducted in future developments, namely:

- Integration with tools that process annual daylight simulations (e.g. Space Series) - this will allow deeper exploration and enhance the capabilities of tools dedicated for annual-based daylight simulations data visualizations.

- Incorporate more design principles from the domain by getting more feedback from experts and conducting usability studies – a tool can only improve if tested by experts of the domain for which it was designed. A set of tests should be envisioned with different architectural and daylight consultant offices in order to get feedback on the flaws and virtues of this approach.
• Incorporate animation to run simulations to show differences over time for each design solution that is being evaluated - animation is a good strategy to show trends over time. In the linking of this tool with annual-based daylight simulation visualization tools, such as Space Series, it could be interesting to animate the heatmaps over a period of time defined by the user. In this way the daylight analyst could have a deeper insight how the patterns change over time.

• Build methods to compare more than 2 heatmaps – right now the tool only compares two solutions at a time. Because in the architectural design field it is common to find sets of alternatives that have more than two solutions, the presented method needs to be extended to contemplate more than two solutions at the same time.

CONCLUSIONS
This paper discussed the limitations of current visualization techniques used in architectural daylight studies. It was observed that current tools and methods do not completely address daylight performance comparison tasks between different design solutions, namely the ones that are based in heatmaps. Therefore it was proposed a tool that implements a method based on the display of spatial heatmaps and more accurate (or at least easier to read) quantitative graph types, such as histograms or boxplots, in a single dashboard. By linking those different graphical displays in a synchronized way the designer has a tool that at the same time can show light distribution patterns and easy to read quantitative graphs of different design solutions. Thus the Daylight Comparison Tool is effective to answer the following questions that arise when an architect finds himself in that crossroads where we needs to choose a solution or a design path: What is the best solution? Where is the best solution better? For how much is the best solution better?

Finally, since this method addresses the comparison of different heatmaps (because they are the most typical visualizations in building daylight simulation) it can be extended to other domains that also use heatmaps extensively. In summary, this paper presented a tool that can compare effectively different heatmaps through a set of interactions and links to other chart types.

REFERENCES