A parametric design-based methodology to visualize building performance at the neighborhood scale

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Abstract

This paper focuses on parametric design-based visualization methods to represent building performance at the neighborhood scale in the perspective of an integrated design-support system. The goal of the developed methodology is to convey the relative effectiveness of different design alternatives according to a wide range of building performance indicators, including the potential for active solar applications, the energy need for space heating/cooling and (spatial) daylight autonomy

The proposed methodology is applied to a case study of a typical urban renewal project in Switzerland for which several design variants were analyzed using validated climate-based simulation engines. For each design variant, simulation results are represented qualitatively using multiple false-color maps and quantitatively through comprehensive plots.

We conclude by showing the applicability of this methodology to a large number of neighborhood-scale design variants as well as the complementarity of the proposed visualization methods. On the basis of the case study application, a possible implementation as a design-support tool is finally discussed.

1. Introduction

The early-design stage often corresponds to the definition of a project at the neighborhood scale, when some of the most important design choices, such as building typology and dimensions, are made. Attia et al. (2009) stress the importance of graphical representation of building simulation results and comparative evaluation of design alternatives at the early-design stage, when architects are usually involved. Haeb et al. (2014) list the typical visualization requirements, including visual feedback on the impact of design decisions, the integration of spatio-temporal analysis and suggestions on design improvements.

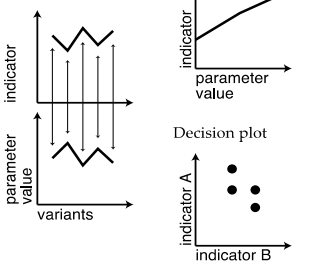
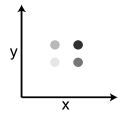
Some building performance simulation (BPS) tools for the early-design phase, like DIVA (Jakubiec and Reinhart 2011), provide spatio-temporal representation of performance metrics in the popular Rhino/Grasshopper parametric modeling environment (McNeel 2013a; McNeel 2013b). The visual evaluation of multiple design variants can be hence obtained through the animation of daylight maps in the 3D scene (Lagios, Niemasz, and Reinhart 2010) or the comparative visualization of energy and daylight results (Doelling 2014). However, such techniques have not been fully applied to urban design yet, as existing scale-specific BPS tools are limited to daylight analysis (Dogan, Reinhart, and Michalatos 2012) or not oriented to parametric design (Robinson et al. 2009; Reinhart et al. 2013).

This paper therefore focuses on techniques to visualize building performance in a neighborhood-scale parametric-design workflow. The case-study application on a typical urban renewal project in Switzerland involved the evaluation of several design alternatives, generated by the variation of building dimensions, using different metrics calculated on the basis of climate-based simulations run in Radiance/Daysim (Ward-Larson and Shakespeare 1998; Reinhart and Walkenhorst 2001) and EnergyPlus (EERE 2013) through the DIVA-for-Grasshopper interface (Jakubiec and Reinhart 2011).

2. Proposed methodology

This section presents a set of six metrics, either directly based on or derived from existing ones, and proposes a unified framework to visualize them at the neighborhood-scale. After a short description of each of them, the approach chosen for their visual representation is provided, and the applicability of these proposals is discussed in the subsequent section. A summary of all metrics and corresponding visualizations is given in Table 8.

Table 8 – The proposed metrics and corresponding visualizations

Metrics	Visualizations
Cumulative	**Comprehensive plots** Variant-performance plot Parameter-sensitivity plot Active Solar energy production Energy Need for space heating/cooling spatial Daylight Autonomy 
Space- and time- varied	**False-color maps** 0 100% Spatial map Solar Irradiation Active Solar suitability Daylight Autonomy  Temporal map temporal Daylight Autonomy

2.1 Cumulative metrics

Cumulative metrics allow for a quantitative evaluation of design variants by providing a value expressing the overall performance of the analyzed buildings over time and space. The ones we present here are particularly suitable for a neighborhood-scale application, as they require only a few parameters to be set.

2.1.1 Active Solar energy production

As an extension of the solar potential concept developed by Compagnon (2004), solar irradiation data is used to estimate the energy production by solar thermal (ST) and photovoltaic (PV) systems.

The irradiation of each simulated surface unit is considered in the metric calculation only if it achieves the thresholds of Table 9. Moreover, a 15% constant efficiency is assumed as a standard value for commercial polycrystalline PV panels, while 70% is considered appropriate for low-temperatures heating purposes using standard flat-plate ST collectors. In order to estimate the surface unavailable for active solar systems (e.g. windows), a surface coverage ratio was set for each system (PV/ST) and each type of surface (roof or façade). Moreover, only surfaces with at least half of the available area achieving the thresholds of Table 9 are considered. These parameters are all included in the metric calculation, as detailed in Peronato (2014).

It should be noted that PV and ST are presumed mutually excluding alternatives, as the appropriate ratio of their usage is usually defined at a later design phase, when energy needs have already been estimated. Therefore, this metric should be considered as a general indicator of the maximum performance of active solar systems, rather than an effective energy production value.

Table 9 – Irradiation lower thresholds for solar active systems (Compagnon 2004)

	PV	**ST**
Roof	1000 kWh/m²	600 kWh/m²
Facade	800 kWh/m²	400 kWh/m²

2.1.2 Energy Need for space heating/cooling

The annual heating (or cooling) load is calculated as «the sum of the hourly heating [or cooling] loads for the one-year simulation period» (ASHRAE 2014) converted from J to kWh and then normalized per conditioned floor area (kWh/m²). This metric corresponds to the Energy Need for space heating and cooling, defined as «heat to be delivered to, or extracted from, a conditioned space

to maintain the intended temperature conditions during a given period of time» (EN ISO 13790: 2008).
Here it is considered as the most appropriate indicator to assess the building thermal energy performance at the early-design phase, when most details about the HVAC system have not been fixed yet.

2.1.3 Spatial Daylight Autonomy

Spatial Daylight Autonomy (sDA) is an indicator of the annual sufficiency of ambient daylight levels in interior environments (IESNA 2012). $sDA_{300/50\%}$ (where the subscript indicates the illuminance goal in lx and the minimum time threshold in %) is defined as the percentage of working plane surface achieving the 300 lx requirement for at least 50% of the occupied times.
It is the preferred metric for the analysis of daylight sufficiency recommended by the Daylight Metrics Committee, allowing comparisons to be made to a consistent standard. Only surfaces achieving $sDA_{300/50\%} \geq 55\%$ are considered adequately daylit (*ibid*.).

2.2 Space- and time-varied metrics

Space and time-varied metrics convey information about the performance of a surface over time. They provide useful information for further design exploration, such as the placement of windows and active solar systems or the allocation of the interior space.

2.2.1 Daylight Autonomy

Daylight Autonomy (DA) is defined as the percentage of the occupied times of the year when the minimum illuminance requirement is met by daylight alone (Reinhart and Walkenhorst 2001).
Even if at the early design phase the building occupancy schedules are usually not fixed yet, as they depend on the specific building functions, the standard occupied hours (8 am to 6 pm) and the illuminance goal (300 lx) suggested by IESNA (2012) were chosen for consistency with the spatial Daylight Autonomy definition as well as to compare the results from different case studies.

2.2.2 Active Solar suitability

In this work, the Active Solar suitability is a binary metric defining whether a surface is suitable for a given active solar system. It is calculated on the basis of the thresholds of Table 9 and of the annual cumulative solar irradiation. The non-null values can be substituted by the actual irradiation, to provide information about the variable degree of suitability.

2.2.3 Temporal Daylight Autonomy

Dynamic daylight performance metrics as the Daylight Autonomy do not include time-based variability, but only retain information about the number of hours when a threshold is achieved. Kleindienst and Andersen (2012) proposed to reverse this approach by using a temporal metric condensing the spatial variation into a single number while displaying variation over time, named Acceptable Illuminance Extent (AIE).
Based on the Daylight Autonomy illuminance target value and the AIE definition, the temporal Daylight Autonomy (tDA_{300}) is defined in this work as the percentage of space achieving the illuminance goal (300 lx) for a given time period.

2.3 Visualization

The analysis of comprehensive plots allows a quantitative comparison of the performance of the design variants and the influence of the different design parameters, while false-color maps give a qualitative assessment of the building performance for further design exploration. Both methods can be combined into an integrated visualization method through the animation of maps and plots.
Finally, by imposing the required design constraints and objectives, the analysis of decision plots is aimed at the selection of the optimal solutions among the simulated design variants.

2.3.1 Variant-performance plots

Variant-performance plots are scatter plots presenting the indicator values (y-axis) for each design variant (x-axis). Multiple plots with the same x-axis scale can be presented in a vertical layout, so as to simultaneously compare the performance of the design variants for different indicators.

The presentation of the parameter variation as an additional plot, with the design variants in the x-axis and the parameter values in the y-axis, allows a visual assessment of the influence of each design parameter on the building performance.

2.3.2 False-color maps

Spatial and temporal maps use the same color gradient to convey information about the achievement of the illuminance goal, respectively, for a particular sensor point over the occupied hours or for a particular number of hours over the surface. A spatial map has Euclidean dimensions for its x and y axes, whereas a temporal plot orders data by day of year (x-axis) and time of day (y-axis).

Spatial maps can be represented either through orthogonal plans or perspective views, in which the simulated surfaces are rendered with a color gradient according to their performance.

Temporal maps were first introduced by Glaser and Ubbelohde (2001) as a complementary visualization to standard spatial plots in a "brushing and linking" method. The temporal-map visualization for illuminance values is limited to one sensor point per plot, unless average values are used. Differently, time-varied metrics allows the visualization of the performance of an entire space in form of one or more percent values while, unlike averaging methods, preserving the understanding of surface variability. The use of temporal maps was aimed at creating a user-friendly method to communicate information generated by daylight simulation to the designer (Kleindienst and Andersen 2012). This is particularly useful for early-stage design decisions, where the specifics of the space are not already defined (*ibid.*).

2.3.3 Parameter-sensitivity plots

Parameter-sensitivity plots represent the performance for a given indicator over the variation of a design parameter. A one-way sensitivity analysis is conducted by visual comparison of such plots.

Provided that the extremes of the axes are fixed according to the range of the design parameters and of the simulation results, the relevance of the parameters in the given range can be evaluated by examining the slope of the curves in the plots: the steeper is the curve, the more influent is that parameter on the indicator's performance. Although this visualization cannot take into consideration the mutual influence of each design choice but only of the selected parameters combinations, it can give an overview of the sensitivity of the indicator based on the variation of each design parameter.

2.3.4 Decision plots

Decision plots are scatter plots in which each axis represents an indicator to be optimized. For minimization objectives (e.g. the Energy Need for space heating/cooling), values are ordered from the maximum to the minimum so as to be compared in the same plot with maximization objectives (e.g. Active Solar energy production).

Decision plots are used to find the optimal solutions as well as to select solutions respecting the given constraints. As long as the indicators used as optimization goals are no more than three, for visualization convenience, the results can be plotted in a 2D or 3D graph in which, for a maximization problem, the most external solutions with respect to the origin of the axes correspond to the non-dominated solutions. These solutions, also called Pareto-efficient solutions, are characterized by the fact that their values «cannot be improved in one dimension without being worsened in another» (Legriel et al. 2010). Restricting the considered variants to the non-dominated solutions allows the trade-off between the objectives to be explored within a smaller solution space, rather than considering the full range of parameters combinations.

3. Application

The *Plan Directeur Localisé Gare-Lac* (Bauart 2010) is an urban renewal master plan in a brown field area of Yverdon-les-Bains (CH). The intent of this case-study application was the evaluation of a large number of parametrically generated design variants in order to optimize solar potential and

built density, while respecting the master plan constraints.

Geometric modifications were equally applied on all buildings through the parametric variation of design parameters within the range of values prescribed by the master plan (i.e. building height), or those considered representative of possible design choices (width and setback). 768 design variants (#1 to #768) were obtained by combination of the parameters defining the height and the horizontal layout of the building blocks (Fig. 1).

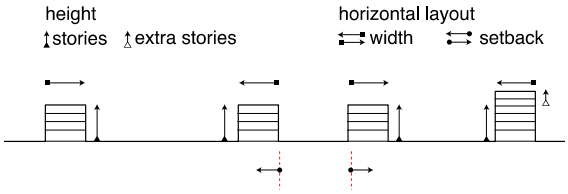


Fig. 1 – Schematic of the parametric model

Due to the computational cost, the simulations were conducted only on three buildings (hereinafter referred to as S, NE and NW blocks because of their relative position in the neighborhood), while taking into account their surrounding context in terms of shading and reflection. For similar reasons, only 32 design variants (#''1 to #''32), defined by a combination of the maximum and minimum values of each design parameter (Fig. 3), were simulated for hourly illuminances.

The metrics were calculated by post-processing the simulation results in custom MATLAB scripts. The generation of plots and temporal maps was also done in MATLAB, while spatial maps were created through the Rhinoceros/Grasshopper interface.

Only results concerning daylighting are presented in performance and sensitivity analyses, as they provide the widest range of visualizations. All results, as well as details on the modeling and simulation phases, can be found in Peronato (2014).

3.1 Performance Analysis

This analysis aims at comparing the trend of performance indicators in relation with the variation of design parameters.

By analyzing Fig. 2 and Fig. 3, it can be noted that block width is by far the most relevant design parameter affecting spatial Daylight Autonomy. Moreover, design variants with the minimum number of stories (i.e. 3) show a better performance, while the extra stories do not seem to be so influential. The influence of setbacks is limited and differentiated. In fact, the north-south setback slightly increases the sDA as it augments the daylight potential on the south-exposed external facades, while east-west setback seems not to affect sDA.

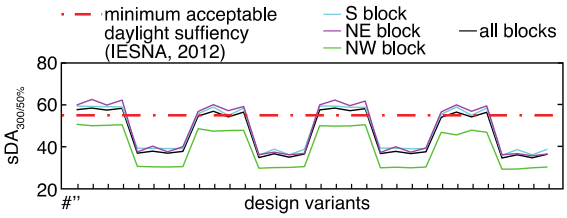


Fig. 2 – Variant-performance plot: spatial Daylight Autonomy

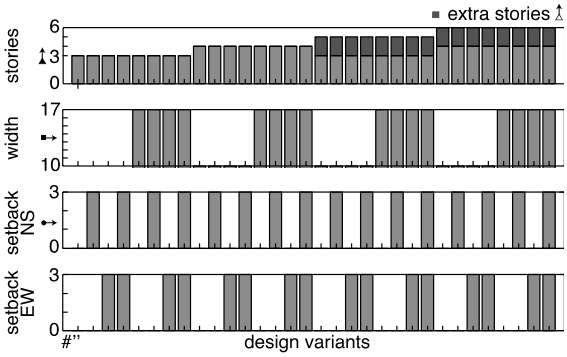


Fig. 3 – Parameter-variation plot: set of 32 design variants

Both spatial and temporal false-color maps are arranged in a parametric matrix (Fig. 4 and Fig. 5) confirming that block width is definitely the most relevant design parameter for daylighting.

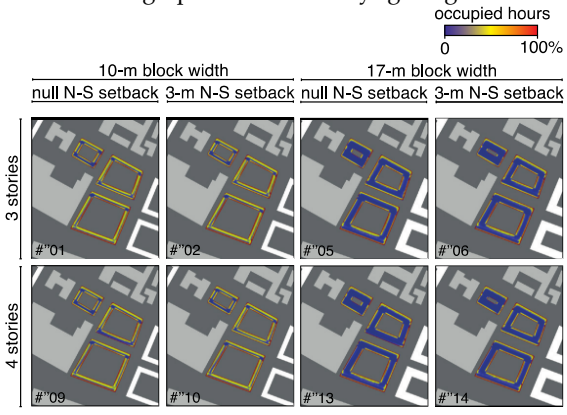


Fig. 4 – False-color spatial maps: DA_{300}

In the spatial maps, it can be noted that the number of stories is particularly crucial for the daylighting of the south side of the north-east block, but a 3-m setback partially compensates the negative effect of the building height, as it can be seen in map #''10.

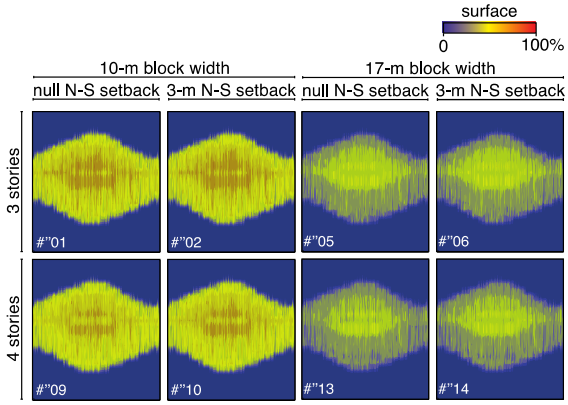


Fig. 5 – False-color temporal maps: tDA_{300}

In the temporal maps, the effect of design parameters is more evident in the time period 12-16 p.m. from April to September for design variants with a 10-m block width (left half side of the matrix), when design variants with 4 stories (second row of the matrix) have a smaller orange area, corresponding to a smaller floor area achieving the 300 lx threshold. However, setbacks contribute to re-increasing the dimension of this area, counterbalancing the negative effect of the building height.

3.2 Sensitivity Analysis

Because of the large number of design parameters, only a few combinations representing the extreme values of each parameter were considered in this analysis.

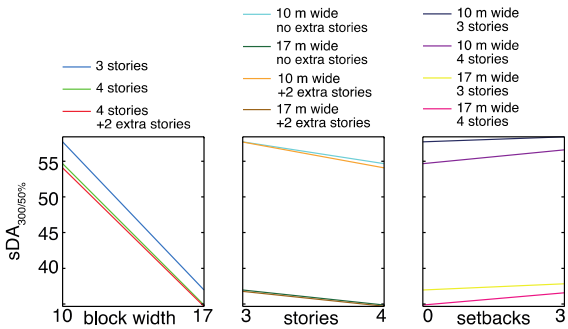


Fig. 6 – Parameter-sensitivity plot: sDA_{300}

In addition to what has already been observed (e.g. the relevance of the block width for daylighting), Fig. 6 shows that augmenting the building height from 3 to 4 storeys has a comparable effect as adding a 3-m setback on 4-storey high buildings, as the curves have similar slopes but opposite angles. Conversely, in 3-storey high buildings, the effect of setbacks is much less relevant.

3.3 Optimization

The selection of the optimal design solutions was done through the analysis of two decision plots.
The decision plot of Fig. 7, in which the space of acceptable solutions is defined by the constraints $sDA_{300/50\%} \geq 50\%$ and Floor Area Ratio (FAR) ≥ 1.7, allows the selection of a set of six acceptable design variants. The density lower limit is a master plan requirement, while the minimum $sDA_{300/50\%}$ was fixed to 50%, as using the minimum daylight sufficiency value (55%) suggested by IESNA (2012) produced an empty solution space.

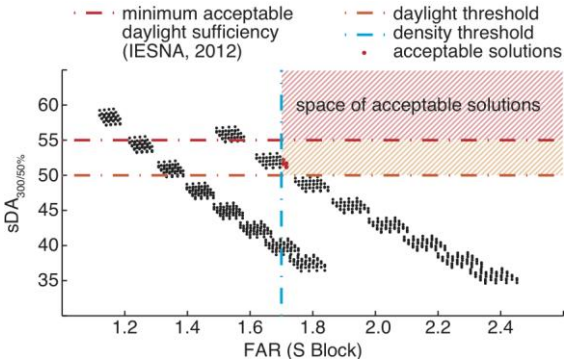


Fig. 7 – Decision plot: selection of the acceptable solutions

The decision plot of Fig. 8 uses the HVAC primary energy (assuming for the heating system a 5% heat losses and, for both heating and cooling systems, an efficiency of 3.1 and a primary energy conversion factor for electricity of 2.0) and Active Solar energy production as the two objectives to be respectively minimized and maximized. It should be noted that all acceptable solutions, previously selected in Fig. 7, show here a low performance for the optimization objectives, while the best solutions, located at the extremes of the axes, do not achieve the density and/or daylight thresholds. However, by restricting the search for non-dominated solutions (as explained in paragraph

2.3.4) to only the acceptable solutions, three design variants (#145, #401 and #657) were selected.

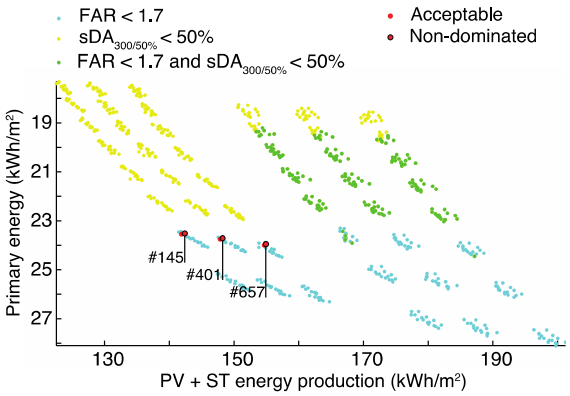


Fig. 8 – Decision plot: selection of the optimal solutions

Table 10 – Parameter values of the acceptable solutions

Variant	Setback NS	Setback EW	Block width	Stories	Extra stories
#145*	0	0	11	4	0
#146	1	0	11	4	0
#401*	0	0	11	4	1
#402	1	0	11	4	1
#657*	0	0	11	4	2
#658	1	0	11	4	2

*non-dominated

Table 10 shows the geometry characteristics of all acceptable solutions, including the non-dominated ones. All design variants present 4 stories (the maximum), an 11-m block width, which almost corresponds to the minimum value (10 m), as well as a null east-west setback. Moreover, the range of north-south setbacks is limited to a 0-to-1-m depth, while all optimal solutions have a null setback. The designer should hence consider these parameters as particularly important for the performance of the buildings, whereas he/she can have a greater degree of freedom in choosing the extra storeys according to other design criteria.

4. Conclusion

This paper has shown a flexible methodology to provide dynamic visualization of the results of building performance simulation for a large number of neighborhood-scale design variants.

The proposed visualizations convey complementary information on the influence of each parameter on the different performance indicators. The false-color maps, for example, help visualize the suitability of each surface and space for different uses, while, at a larger scale, sensitivity analysis highlights the relationship between each design parameter and building performance indicator, so that the designer is more conscious of his/her choices. Finally, the decision plots allow the designer to visualize the optimal solutions for some given objectives and constraints among the whole set of simulated design variants. However, in the case-study application, only a few variants were acceptable for the chosen constraints, while presenting among the poorest results for the optimization objectives. This proves that optimization is first of all a question of priorities and that the choice to be made by the designer (or the decision maker) about which objective(s) to give priority to is fundamental.

The main limitations of the methodology are linked to the computational cost of simulations, in particular those of interior illuminances, as well as to the assumptions made for the metrics calculation. Further work should be done to implement the proposed workflow in an interactive design-support system and to verify its effectiveness in a usability testing study. The support in the choice of parameters and their range of values through a first evaluation of simpler metrics would limit the use of time-expensive simulations. Such a platform should be finally released as a standalone software or plugin to be used in real design practice.

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