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DAYLIGHT PROTOTYPES: FROM SIMULATION DATA TO FOUR-DIMENSIONAL ARTEFACT

Physical metrics models in sustainable design education

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Abstract. The increasing use of building performance simulation in architectural design enriches digital models and derived prototyping geometries with performance data that makes them analytically powerful artefacts serving sustainable design. In our class "Parametric Design", students perform concurrent thermal and daylight optimization during the architectural ideation process, employing digital simulation tools, and also utilize rapid prototyping techniques to produce process artefacts and whole-building analysis models with climate-based daylight metrics physically embedded. Simulation metrics are merged with prototyping geometries to be output on a colour-capable Zprinter; the resultant hybrid artefacts simultaneously allow three-dimensional formal as well as whole-year daylight performance evaluation, rendering analysis scope four-dimensional. They embody a specific epistemological type that we compare to other model instances and posit to be an example of multivalent representation, a formal class that aids knowledge accretion in performance-based design workflows and allows designers to gain a physically reframed understanding of geometry-performance relationships.

Keywords. Rapid prototyping; building performance modelling; daylight simulation; physical data models; design representation.

1. Introduction: Rapid Prototyping and Performance Simulation

Digital design media has undergone several decisive paradigm changes throughout the last decades. The shift from two-dimensional CAD to parametrically responsive, data-enriched digital models has evolved the perception of architecture-in-progress from a play of static representations towards the interaction with dynamic codifications of constraints and form. In parallel, rapid prototyping (RP) techniques have established a direct link with subsets of the material realm. These developments have fundamentally influenced the way architectural design is practiced, taught and researched, both on the level of design epistemology and in the way representative process artefacts are understood (Sass and Oxman, 2006). With the formal and functional possibilities of the dynamic ideation-production complex tentatively established, attempts are currently being made under the auspices of sustainable architecture to integrate simulation-based performance prediction into the mainstream of environmental design activities (Venancio et al., 2011; Hetherington et al., 2011). Consequently, RP models become linked to simulation data sources, yet still exist as their own epistemological category. How data-rich design environments can imbue them with additional representational and analytical properties is explored in this paper; previous work on data-embedded prototypes performed at the Milwaukee School of Engineering acts as proof-of-concept precedent (Bolda, 2008).

1.1. CLASS BACKGROUND AND PAPER STRUCTURE

The class "Parametric Design", during which the 1:250 scale daylight models presented in this paper were generated, teaches energy and daylight simulation in a design context. Students create their own building layouts, in the discussed semester based on the brief of an office building. They improve energy efficiency and daylight utilization by means of adapting architectural form using DesignBuilder, an interface to the simulation engine EnergyPlus (Crawley et al., 2000), and DIVA (Jakubiec and Reinhart, 2011), a daylight simulation plugin for the modeller Rhinoceros3d.

One of three sites in different climate zones (Östersund, Sweden; Hashtgerd, Iran; Ft. Lauderdale, Florida, USA) is to be individually chosen by students, resulting in designs that are in massing and envelope visibly attuned to the respective environmental conditions. Studies of alternative construction materials and passive conditioning are not part of the class, since it is primarily concerned with the comparative effects of building geometry. As such, the final artefacts built by students would in reality likely not reflect the last iteration but instead serve as an evaluation milestone; the models are thus regarded as in-process representations outlining intended form.

Three main assignments take students through the design-optimization process, beginning with heuristic design seed generation, continuing with partial simulations and finally encompassing whole-building calculations. Optimization is achieved by investigating geometric properties like orientation, window-to-wall ratio changes and fixed shading devices. Despite featuring iterative evaluations, integrated design is usually not a linear or rational activity, as previously reported by the authors. Instead, cross-domain representations serve to continuously enrich form-performance knowledge, which in return improves heuristic decision-making (Doelling and Nasrollahi, 2012). The artefacts discussed

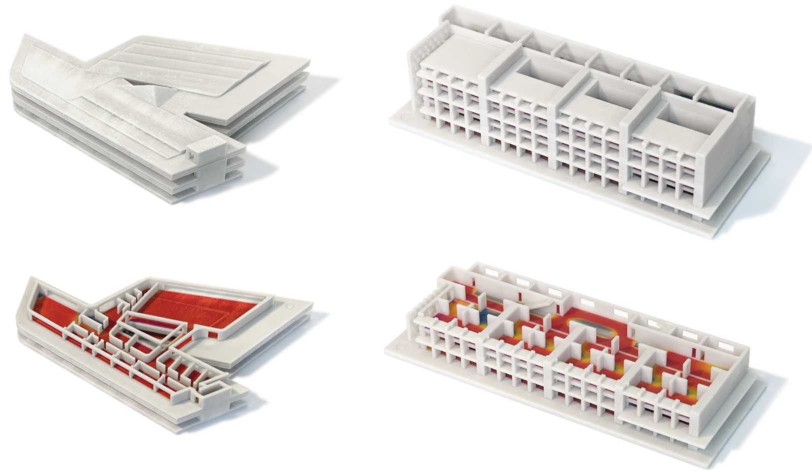

Figure 1. Rapid-prototyped daylight models, Florida (left) and Iran (right), with DA 300 and UDI 100–2000 lux metrics embedded.

herein accompany this process; whole-building metrics models are preceded by test geometries to gradually approach a holistic design state. This paper presents two physical daylight models (Figure 1), their prior test artefacts and positions them in the overall workflow. It provides the theoretical background of daylight simulation and explains model production. Finally, we derive the models' representational and processual properties and discuss their usefulness for sustainable design.

2. Daylight Prototypes: General Properties

Since light behaves identically at life-size and model dimensions when surface properties are analogous, simulation scale models have been used extensively in architectural design. Digital daylight evaluation has now surpassed previous methods in analytical scope, hence main simulation work in our class is performed by computing climate-based daylight metrics that display the percentage of inhabitant-occupied hours of a whole year when illuminance meets a set target (Reinhart and Wienold, 2010). The prototypes show the metrics "Daylight Availability" (DA) in office spaces, tuned to 300 lux as per IESNA recommendation (Rae, 2000) and "Useful Daylight Illuminance" (UDI) 100–2000 lux embedded in non-office spaces with varying daylight requirements. UDI values of 100 to 2000 lux, which are generally useful (Nabil and Mardaljevic, 2006), describe an illuminance range that indicates the remaining zones' overall daylight potential.

In the model-embedded metrics, orange to red colours denote good performance (ca. 70 to 100% of occupied time target illuminance reached), while yellow to blue for UDI spaces indicates either partially overlit or underlit conditions. Pink colours in the DA metrics show areas that exceed 300 lux at least 5% of yearly occupied hours, with underlit areas indicated as in the UDI scheme. Results are shown with no additional dynamic shading devices used, which stays in tune with class intent: a building that by its geometric nature reduces the overall occurrence of overlit areas offers a better starting seed for further optimization work. Surface reflectances and visual transmittance values, however, are fully accounted for.

To facilitate viewing of all spaces, models can be disassembled, inviting them to be handled; a north arrow is included in each base, since knowledge of a building's orientation is essential to understand performance.

2.1. INDIVIDUAL DAYLIGHT PROTOTYPES

Out of the many models produced, we discuss designs situated in Iran and Florida. The annual average dry bulb temperature in Ft. Lauderdale is 25° C; intense insolation occurs the entire year (1792 kWh/m^2 cumulative horizontal irradiation), with summer tendentially overcast; in winter, direct sunshine prevails. Providing continuous shade and attenuating sunlight is important for daylighting purposes and to reduce cooling energy consumption.

The design (Figure 2) features large overhangs that shade all façade orientations and double as a continuous balcony; light is scattered by additional horizontal louvers into a diffuse field that still allows for comparatively large window openings usable to achieve cross-ventilation.

In initial versions, vertical louvers were proposed and physically tested with a selectively laser-sintered model. Successive digital simulations further investigated their performance and the effect of varying overhang widths, revealing that using horizontal louvers only yields best results. Additional North-facing skylights allow for deep daylight penetration with low thermal trade-offs, further aided by a shielded courtyard acting as a light-well. Total projected energy demand for heating, cooling and lighting was reduced throughout the design process from 111 kWh/m^2 to 68 kWh/m^2; final DA 300 lux utilization is 84% of occupied hours, UDI 100–2000 90%.

The second design is situated in Hashtgerd, Iran. Clear skies predominate (1951 kWh/m^2 cumulative horizontal irradiation) and strong seasonal temperature variations exist, giving an average annual dry bulb temperature of 15°C. Thermal solar gains are welcome in winter and to be prevented in summer. Thus, the envelope looks entirely different (Figure 3), also a result of the solar geometry at Hashtgerd's more northern latitude.

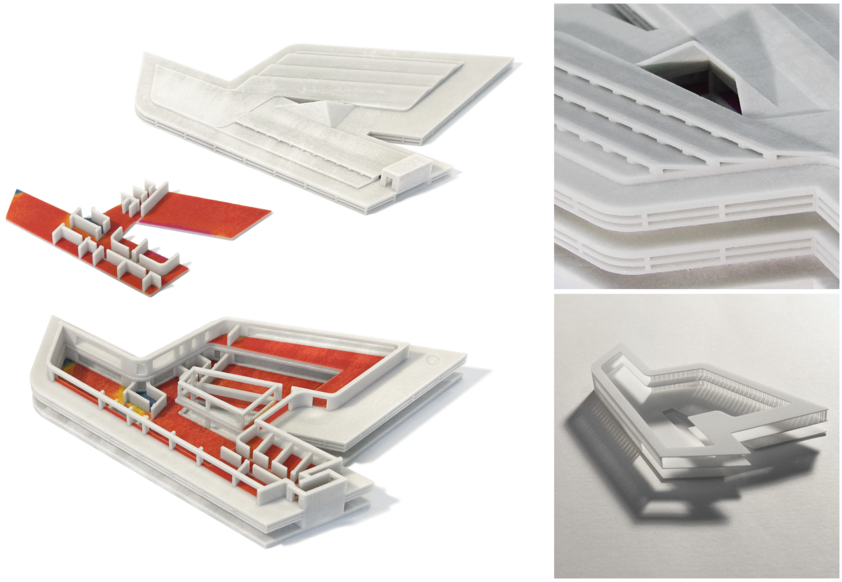

Figure 2. Florida sintered test model, skylight/louver detail and final RP model shown disassembled with DA 300 and UDI 100–2000 lux metrics visible.

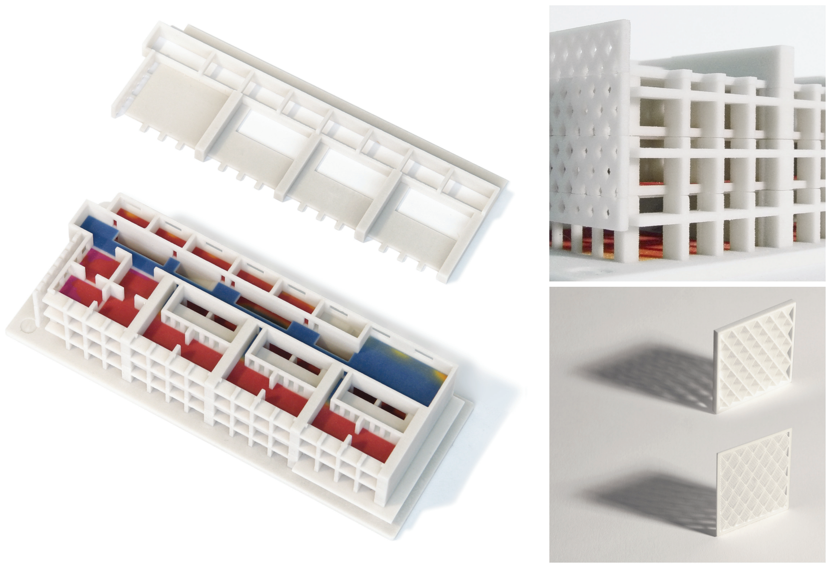

Figure 3. Iran sintered shading geometries, facade detail and final RP model shown disassembled with DA 300 and UDI 100–2000 lux metrics visible.

A key design strategy is the use of a south facade that is deep in section. Fixed overhangs and fins shield from high altitude, glancing angle summer sunshine, and overhangs additionally act as light shelves to increase daylight depth. In effect, the average yearly daylight distribution is excellent, however seasonally more varied than in the Florida design and exhibiting some overlit areas due to low winter sun angles.

A large atrium along the building's spine allows light to reach the second-storey back offices, which also receive illumination from skylights. Prototyping tests additionally focused on a diamond-grid shading structure on the West façade, intended to allow views and limit summer gains, which was iteratively laser sintered and tested in several independent variations, ultimately influencing the façade layout. Total heating, cooling and lighting energy demand was reduced from 54 kWh/m^2 to 46 kWh/m^2; daylight utilization is 70% for DA 300 lux and 78% in the UDI 100–2000 range.

3. Process: Data Preparation and Model Production

The class workflow relies on the parallel use of thermal, daylight simulation and conceptual design models. It constitutes a heterotopia of tools and representations specific to the epistemological interest at hand; how their domain of permutations is navigated has decisive influence on the simultaneous discovery and actualization of design intent. In general, students attempt to align spatial parameters with specific simulation investigations by means of synthetic representations; performance and form are judged in unison, mediated by simulation data embedded in digital and RP models.

The plugin DIVA links the dynamic daylight simulation tool Daysim (Reinhart, 2006) to Rhinoceros3d. It employs a daylight coefficients approach (Bourgeois et al., 2008) to numerically encode the mediating effect building geometry has on the ability of virtual sensors to receive specific fractions of sky luminance during each hour of the year. This allows sets of new metrics to be generated quickly if occupancies and illuminance targets shift. EnergyPlus weather files comprised of real-world measurements are used, identical to the ones employed for the thermal simulations. These files describe typical site conditions taken from multi-year data (Wilcox and Marion, 2008).

Simulation models are built as 1:1 scale NURBS geometries in Rhino and usually also serve as conceptual design models; they share analogous quality requirements with derived RP models, most importantly topological mesh validity and avoidance of coplanar surfaces. Daysim requires polygon mesh input, therefore complicated geometries were often pre-meshed for precise export, a step that must also be performed with RP geometries. These similarities establish a layer of logical workflow connections that semantically unify the production process. Before prototyping, students commonly rebuild geometries at model scale to maintain a balance in proportions, in itself an aesthetic decision, and as prefiguration of desired tactility chose which parts of the model are to be made detachable. Daylight metrics textures are derived from DIVA results grids, in Rhino 5 assigned to densely triangulated floor planes and baked into the vertices to remain fixedly embedded.

Gypsum-based RP models are printed layer by vertical layer; clear and coloured binder is sequentially deposited on a proprietary substrate that is spread over the build area to materialize each model slice. Special consideration is given to the used ZPrinter's specifications, e.g., avoidance of features less than approximately 1.5mm in thickness, as they are too sensitive to handle in post-processing. The physical artefact is fragile upon removal from the machine and needs to be sealed with clear, low viscosity epoxy; this procedure gives models the desired robustness to withstand continuous handling, one of their important properties.

4. Conclusion: Model Epistemology and Design Education

Having described the class background, select prototypes and production procedures, we now need to synthesize the models' properties and elucidate their applicability in the practice of sustainable design education.

Simultaneously negotiating a multitude of epistemes to achieve design performance actualization poses the challenge of managing the interplay of various evaluative representations. In order to achieve a semantic transfer of cross-domain information, the expressions of tools, workflows, metrics and their intended impact on design decisions need to be seen in unison, as posited in integration research (Mahdavi, 2011). In our case, the involved domains are design and daylight/thermal optimization, both enmeshed as a work-in-progress. The multi-tier strategy of articulating several assembly prototypes first, before producing the complete final models, is closely related to a workflow that relies on the steady accretion of form-performance knowledge and cannot be described in linear terms; as such, the RP models are snapshots of design intent at different advancing stages and aid the ideation process by combining spatial expressions with performance indicators.

The similarities of simulation and prototype geometry preparation bind both activities into a single, comparatively seamless space, however it is primarily the final models' properties and contained information that gives them their descriptive acuity. Traditional physical models can serve to elucidate a finished design or be used as process tools (Moon, 2005), however usually do not contain

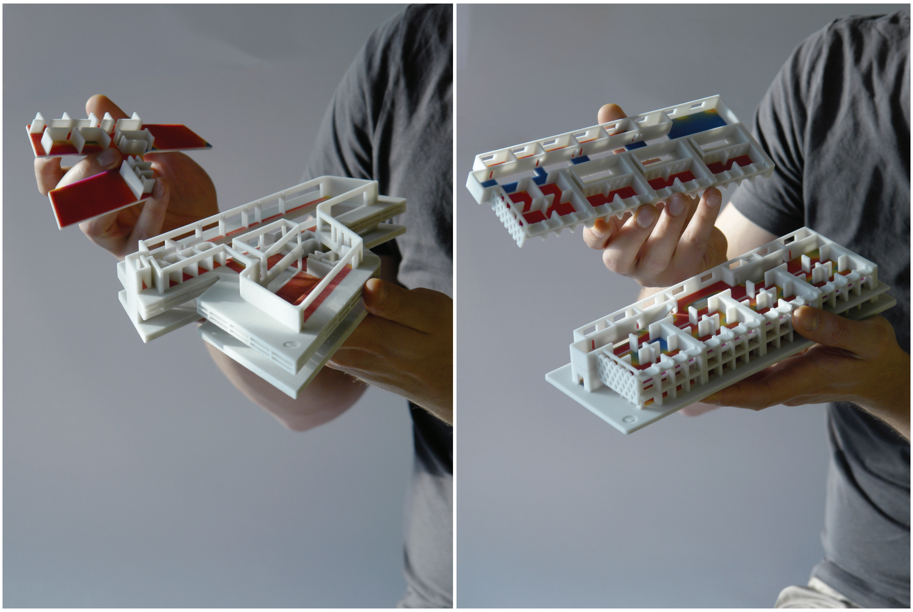

Figure 4. Florida, Iran daylight models handled and disassembled, daylight metrics visible.

performance projections. Since no advanced daylighting implements such as light-redirecting glazing or dynamic shades are used in the prototypes, their physical expression directly references the main geometric features responsible for performance. This absence of invisible modifiers lends them strong immediacy and analytical presence; only glazing transmittances and surface reflectances are not materially reproduced, yet in the discussed models have a much reduced impact on performance compared to their overall geometric properties. In-process simulation data is commonly displayed through the filtering effects of digital, projective design media; the prototypes instead allow non-projective, three-dimensional and factually invariant perception while retaining dynamic engagement, since their separation into parts and physical stability invite interaction (Figure 4).

Additionally, the climatic information used to generate the included daylight metrics contains the typical conditions at a site, not only those for one year. Hence, the prototypes become four-dimensional, since they refer to location-specific performance over time, which cannot be physically shown by artefacts not enriched with simulation data. The illuminance target specificity of the used DA and UDI metrics can also not easily be represented in traditional physical models and is unique to the RP geometries.

In summary, the metrics models enable management of multi-domain data from design and engineering epistemes by splicing together features of the architectural model, a classic representative category that principally investigates form, with data from the engineering domain of energy performance optimization; as descriptors, the models are thus truly multivalent and reflect a field state of design thinking at the end of the schematic design phase, for they allow a simultaneous, three-dimensionally mediated observation of performance and the geometrically encoded design decisions that are its cause.

4.1. MODEL APPLICABILITY IN DESIGN EDUCATION

We intensively use previous models in following classes as they make the interplay of performance and geometry literally graspable for students, summarize optimization results in a physically reframed shape and serve as a typological library. The handwriting of manual model-building is partially erased by the modes of digital fabrication that reduce designs to geometric purity, yielding precise yet abstract expressions on which new ideas can be projected. This also simplifies morphological comparisons between multiple printed prototypes across several climate zones, which is the explicit goal of our class; thermal design considerations are geometrically implied and become most apparent when directly comparing several artefacts. Also, overlit areas are often correlated with unwanted solar gains, which become visibly pin-pointed in the models. New students are thus exposed to an intuitive demonstration of geometry-performance interplay; despite no legend being included on the artefacts, when presenting them with a quick remark that “red means good performance”, observers usually quickly grasp the way a given design controls solar gains and achieves good daylight performance.

In essence, the models aim to educate upcoming class participants as much as they do the original creators, who additionally deepen their knowledge by prototyping selective performance artefacts such as the sintered façade studies also shown in this paper. These offer an experience of point-in-time shading behaviour and are then, in modified fashion, implemented in the whole-building designs, their annual performance to be finally encoded in the whole-building prototypes. As we commonly experience in teaching, projective graphical metrics display on screen or as numerical data requires much greater explanatory effort than demonstrations based on physical artefacts. The models’ ultimate power therefore lies in enhancing the understanding and communication of a specific design state as well as improving the way further adaptations are envisioned. Their meaning is readable on several epistemological levels at once, expressing more than the sum of individual parts: design synthesis.

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References

Bolda, J.: 2008, “Rapid Prototyping: A Sustainable Design Aid”, REU research paper, Milwaukee School of Engineering.

Bourgeois, D.; Reinhart, C. F. and Ward, G.: 2008, A Standard Daylight Coefficient Model for Dynamic Daylighting Simulations, *Building Research & Information*, **36**(1), 68–82.

Crawley, D. B., Pedersen, C. O., Lawrie, L. K. and Winkelman, F. C.: 2000, EnergyPlus: Energy Simulation Program, *ASHRAE Journal*, **42**(4), 49–56.

Doelling, M. and Nasrollahi, F.: 2012, Building Performance Modeling in Non-Simplified Architectural Design, *Proceedings of the 30th eCAADe Conference*, Prague, 97–106.

Hetherington, R., Laney, R., Peake, S. and Oldham, D.: 2011, Integrated Building Design, Information and Simulation Modeling: The Need for a New Hierarchy, *Proceedings of Building Simulation 2011*, Sydney, 2241–2248.

Jakubiec, J. A. and Reinhart, C. F.: 2011, DIVA 2.0: Integrating Daylight and Thermal Simulations using Rhinoceros 3D, Daysim and EnergyPlus, *Proceedings of Building Simulation 2011*, Sydney, 2202–2209.

Mahdavi, A.: 2011, The Human Dimension of Building Performance Simulation, *Proceedings of Building Simulation 2011*, Sydney, K16–K33.

Moon, K.: 2005, *Modeling Messages: The Architect and the Model*, The Monacelli Press, New York.

Nabil, A. and Mardaljevic, J.: 2006, Useful Daylight Illuminances: A Replacement for Daylight Factors, *Energy and Buildings*, **38**(7), 905–913.

Reinhart, C. F.: 2006, *Tutorial on the Use of Daysim Simulations for Sustainable Design*, Institute for Research in Construction, Ottawa.

Rae, M. S.: 2000, *The IESNA Lighting Handbook. Reference & Application, 9th Edition*, IESNA, New York.

Reinhart, C.F. and Wienold, J.: 2010, The Daylighting Dashboard – A Simulation-Based Design Analysis for Daylit Spaces, *Building and Environment*, **45**(8), 2440–2457.

Sass, L. and Oxman, R.: 2006, Materializing design: the implications of rapid prototyping in digital design, *Design Studies*, **27**(3), 325–355.

Venancio, R., Pedrini, A., van der Linden, A. C., van den Ham, E., and Stouffs, R.: 2011, Think Designerly! Using Multiple Simulation Tools to Solve Architectural Dilemmas, *Proceedings of Building Simulation 2011*, Sydney, 522–529.

Wilcox, S. and Marion, W.: 2008, *User Manual for TMY3 Data Sets*, Golden, National Renewable Energy Laboratory.