Building Performance Modeling in Non-Simplified Architectural Design

Procedural and cognitive challenges in education

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Abstract. *The building technology class "Parametric Design" simultaneously teaches thermal and daylight performance simulation to novice users, usually Master of Architecture students. Own buildings are created, analysed and geometrically modified during the design process, resulting in structures that are energetically pre-optimized. It is shown that energy demand and daylight utilization can be significantly improved while taking into account formal considerations. Departing from a design process model that gives preference to either engineering or design thinking, multi-modal decision-making is diagnosed to be mediated by hybrid or multivalent representations, necessitating a shift in how inter-domain design knowledge flows might be understood. Opposed to purely linear or iterative process assumptions, a fluent state model of interconnected domains of analytic inquiry is proposed.*
Keywords. *Sustainable design; daylight simulation; thermal simulation; architectural education; design epistemology.*

INTRODUCTION

Digital, parametric model-based design workflows offer many opportunities to integrate performance simulation into the architectural design process, but as a relatively novel practice, no proven set of design methods or cognitive framework has yet been established. Many traditional simulation classes consider simplified design parameters and produce results that stream towards clear performance indicators. While entirely appropriate, and possibly even reflects a large aspect of the built environment's formal reality, an increasing tendency exists to strive towards forms that are not intended as mere aesthetic experiments but to enrich the lives of inhabitants through enhanced comfort. In this context, our ongoing seminar "Parametric Design" investigates the integration of multiple building performance simulation techniques into the early stages of architectural design. Master of Architecture students with minimal or no knowledge of building performance simulation are tasked with expressing a functionally diverse spatial programme, using daylighting and thermal assessment tools as continuous design decision benchmarks. One of three sites (Berlin: Germany, Hashtgerd: Iran, Ft. Lauderdale: Florida, USA) has to be chosen, yielding designs specific to the local climate but related through their shared design brief. Basic lectures on sustainable building and simulation principles are given, while workshops

introduce students to the interlinked usage of DIVA (Jakubiec and Reinhart, 2011), a daylight simulation plugin for Rhinoceros3d, DesignBuilder, an interface for the simulation engine EnergyPlus, Rhinoceros3d, a NURBS modeler, and Grasshopper3d, a parametric geometry tool.

PRECEDENTS IN DESIGN-SIMULATION INTEGRATION

Various different models of building performance simulation classes are described in the literature, as are approaches that deal with integrating simulation into the architectural design process in general. The following selection is not intended as a comprehensive classification of previous studies, but instead serves to position our own endeavor within this developing field.

Many simulation classes cater to architecture students and contain a design component, the analysis of which can then also be related to tool use considerations (Palme, 2011). Alternatively, unconstrained architectural design activity is frequently not part of a class (Strand, Liesen and Witte, 2004; Madsen and Osterhaus, 2005). Epistemological workflow considerations are discussed from various angles, usually contrasting engineering and design working methods, or attempt to establish intermediate ground (Batty and Swann, 1997; Hetherington et al., 2011; Venancio et al., 2011). Most case studies acknowledge the importance of early-stage architectural energy optimization through design, yet our review indicates that it is the norm for only one simulation domain to be detailedly taught per class, unlike in our own, which introduces both daylight and thermal simulations in an integrated manner. In this paper, we touch on tool use implications, but assume the chosen software applications to be reliably useable in the design process due to advanced interfaces, precise results display and their use of the validated simulation engines EnergyPlus and Radiance. In essence, we attempt to understand possible modes of simulation-assisted cross-domain decision-making by architectural designers performed from the very first creation steps to the end of the schematic design phase, since in this time frame fundamental, difficult to reverse choices affecting form and energy use are made (Brown and DeKay, 2001). No normative workflow recommendations will be stated; instead, analyzing various process representations in conjunction with describing decision chains will lead us to an alternative integrated design process model.

RESEARCH QUESTIONS

The following sections introduce the curriculum employed by us, present two class results from summer 2011 and relate them to the challenge of integrating building simulation into early-stage architectural design. The guiding research questions are:

1. Are simulation activities easily effective in decreasing a design's primary energy demand if they are to be positively correlated with making desired formal decisions, in a process that acknowledges functional and geometric complexity?
2. How are design decisions made in a multi-representational domain that includes parametric performance models?
3. What consequences might the results and the modes of their making have for architectural education and design theory?

CLASS ORGANIZATION

The seminar investigates design-simulation process interaction by posing a "real-world" problem. There are no rules concerning the building shape, albeit we ask students to consider the task realistic in the sense of a limited budget and apparent constructability of the 804 m^2 community center. Spaces are a mix of offices, seminar rooms and a small auditorium. By having students design in different climate zones, they experience how buildings that share the same design brief are morphologically influenced by adapting to the local climate.

CURRICULUM, ASSIGNMENTS AND DESIGN OBSERVATIONS

The course assignments are modeled after the hier-

archy traditionally found in design studios, with energy optimization primarily to be achieved through architectural instead of technological means. Hence, formal and performance decisions are closely related (Nasrollahi, 2009). Our following process narrative is a temporally linear approximation of groups' design thinking at various advancing stages, as interpreted by the authors based on tutoring, results data evaluation and representation analysis.

Heuristic and initial simulation phase

Assignment 01 asked students to start design work and to especially consider early stage performance rules of thumb, requiring them to document key design concepts relating to the intended environmental performance in principle sketches that should relate to the local climate. Group 01 chose Ft. Lauderdale as the project site; group 02, chose Hashtgerd, Iran. The climates of both sites are very different: Florida's low latitude, low elevation and proximity to the Gulf of Mexico lend it year-long high temperatures, mostly uncomfortable in summer due to high relative humidity, while Hashtgerd's more northern latitude, higher elevation and greater distance from the ocean yield a continental climate with both summer and winter discomfort extremes. The goal of performance design strategies was to minimize the primary energy demand of heating, cooling and lighting equipment required to achieve thermal and visual comfort.

In the initial phase, a massing approach (figure 1) and response to site conditions was defined, with most groups departing from and modifying the basic principles thus discovered throughout the class. Design rules of thumb were recommended to be followed from various publications (e.g. Brown and DeKay, 2001) and Climate Consultant, a climate analysis package. The very earliest design stage, articulated by sketches (figure 2) and arrays of incomplete models, featured too little information to enable simulations that require defined geometries. Only at its end was a base layout established, on which first analyses were performed. This marked the transition from purely heuristic to partially evidence-based modes of thinking.

Assignment 02a dealt with running climate-based daylight simulations (Reinhart, Mardaljevic and Rogers, 2006) and a seasonal cumulative solar irradiation analysis, achieved with DIVA. The reason for considering insolation images and daylighting first was our intention to have students visually experience solar gains, with the hope that they would tweak their assumptions on solar geometry and arrive at an improved building layout before constructing thermal simulation models.

Group 01 correctly identified horizontal as well as east and west facing surfaces as major receivers of insolation (figure 3). This was in part caused by

the massing strategy chosen due to wind patterns and spatial organization considerations, which were also related to assumed daylighting benefits tested

Figure 1
Natural Ventilation and Massing Sketch, Florida Design.

Figure 2
Design Development Sketches (Plans roughly oriented north), USA.

Figure 3
Summer / Winter Irradiation Images (South to left of frame), USA.

through simulations and found to be promising (figure 4). The design process in all coming phases then evolved towards a systematic evaluation of different facade structures, many of which were not iteratively related but formal experiments and performance assessments in unison. Aesthetic requirements of retaining vertical fins to visually balance the horizontal massing scheme were expressed by the group throughout the class, setting a formal parameter space within which most explorations were achieved. The authors found that this happened in the case of most groups; the final solutions frequently showed an expression of ideas developed during the heuristic design development phase.

The Iran team ran site-level irradiation simulations via Ecotect and chose a site patch with maximum insolation to receive their design, intended as a compact volume tilted towards lower sun angles (figure 5). Despite at first glance promising, it later became apparent that this systematic initial approach yields no guarantees that building performance will actually be superior to rule of thumb only approaches, since when site-level analyses are performed without preconceived ideas on the structure to be designed, no relationship between measured site phenomena and building geometry yet exists.

Interior spaces were arranged into a dense layout situated under a slanted roof perforated by skylights. The handling of these apertures was the key geometric element affecting design performance; they developed from simple horizontal openings to complex solar scoops, their behavior parametrically defined by flexible Grasshopper3d-definitions. Insolation analysis performed on various scoop tilts resulted in the group choosing an angle that caused greater gains in winter and relative prevention of direct sunlight penetration in summer (figure 6). In that sense, the irradiation images played a greater role in meshing thermal optimizations with formal considerations, and thus acted more as a useful tool than they did for group 01, who argued from a different set of constraints, especially wind patterns and projected daylight demand. Group 02's

approach can hence be understood as having been more driven by thermal performance concerns; the observed useful daylight utilization of the first iteration was indeed sub-par (figure 7).
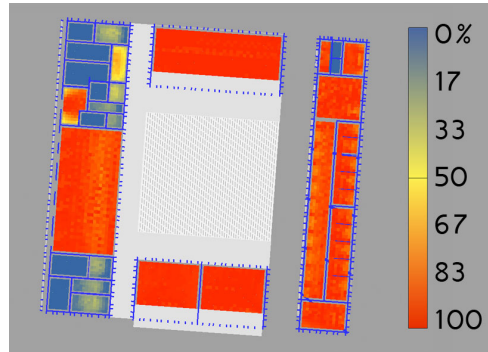
Figure 4
Variant 01 (Florida), Useful Daylight Illuminance, 100 – 2000 lux, % of occupied hours, fixed louvers.
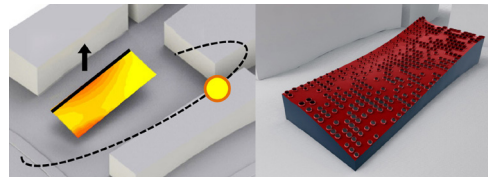

Figure 5
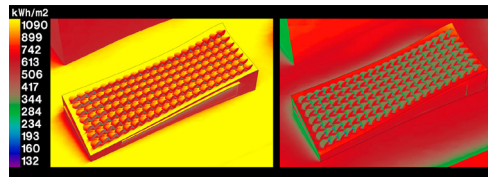Site Irradiation Analysis & Volume Derivation, Iran Design.

Figure 6
Summer / Winter Irradiation Images (North to top of frame), Iran.
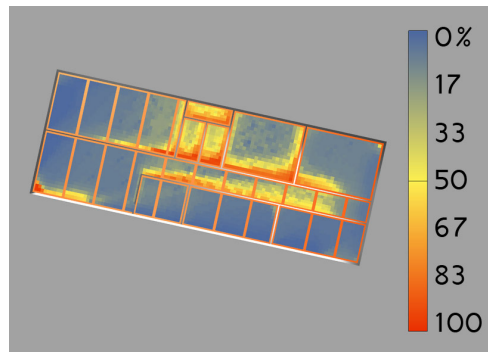

Figure 7
Variant 01 (Iran), Useful Daylight Illuminance, 100 – 2000 lux, % of occupied hours, no shading.
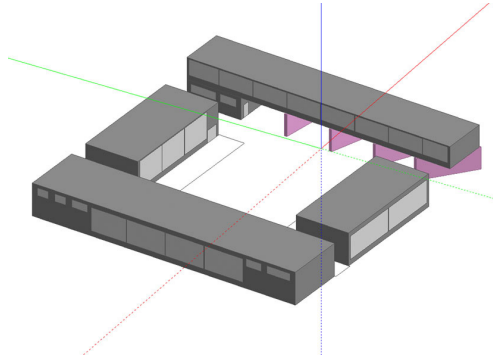
Figure 8
DB Model, Variant 01, USA.

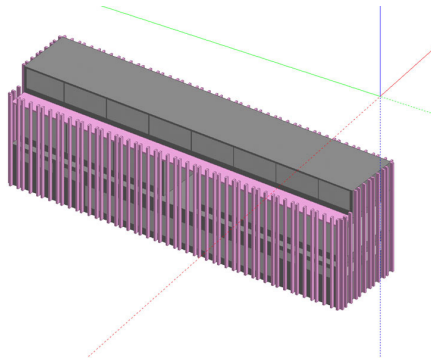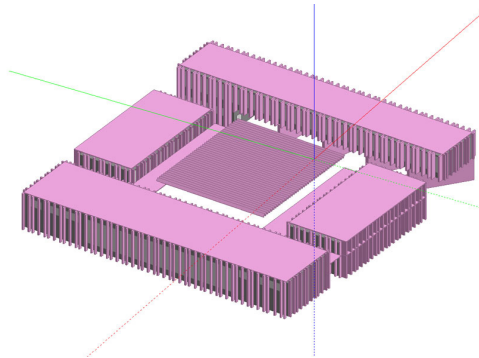Figure 9
DB Model, Variant 02b.

Figure 10
DB Model, Variant 03.

Detailed simulation phase

Assignments 02b and 03 required students to adapt their designs through DesignBuilder (DB) and further DIVA simulations. Alternate massing strategies had to be considered in step 02b; in assignment 03, the best performing massing variant in terms of primary energy demand and daylight utilization was to be chosen and several design factors systematically varied to arrive at a final proposal, its energy and daylight performance to be fully analyzed. By keeping simulated physical building materials, occupancy information and assumed best-practice HVAC templates constant throughout the class and concentrating on changes on the level of orientation, massing, glazing ratios and fixed shading geometries, the direct influence of form on performance was studied; yet in practice, initial decisions usually overrode the possibility of fundamental changes. Most groups found it hard to divorce their thinking from the version already created and to define an alternate massing scheme.

Expressing the desire to retain the initial design, group 01 departed from an unshaded base design (figure 8) and especially studied the effects of side-fin shading geometries and ventilated double-roof structures (figure 10) on total energy demand, reducing it by 30%. Gross daylight utilization was improved 15% by using light shelves and modifying fin spacing (figure 11). Light shelves were used for all but the North orientations and additionally acted as overhangs (also see figure 20). Simulation results are summarized in figure 15, clearly showing an increase in overall design performance. The required alternate volumetric scheme of variant 02b (figure 9) did not have an impact on subsequent design decisions, possibly due to its negligible performance improvement and seemingly improvised layout.

Group 02 did not produce an alternate massing scheme, but instead focused on the spacing, arrangement and glazing area of the skylights, also starting from a base design (figure 12). The number of aperture rows in the final iteration was reduced by three and the total glazing area more than halved (figure 13), which lessened total energy demand

by 25% and almost doubled useful daylight utilization (figure 14). An increase in skylight row spacing meant a reduction of winter overshadowing effects; this change was stimulated by knowledge gained from the previous irradiation image analysis.

There was considerable geometric drift between the individual design and simulation models, as well as strong abstractions present in the thermal models. The most pronounced difficulty lay in how to port the light scoop geometries between daylighting and thermal models; this was solved by synchronizing the glazing area and building custom overhangs in DesignBuilder, which imitated the scoop tilt as used in the Grasshopper definition. Opposed to the Florida team, who performed intermediate daylighting tests on singular geometric expressions and generally kept DB and Rhino models parallelized, group 02 used several thermal geometry variants independently. Two series of models with a stepped decrease in scoop glazing area were compared and the results fed back into the original parametric geometry definition (figure 16). As such, an iterative workflow was contained within a formal parameter space, which was itself dynamically encoded and eventually updated to reflect the final analysis step.

Naturally, the groups' results in both simulation domains could be improved, yet by limiting material choices to elucidate the effects of form and being constrained by what simulation novices can accomplish in a single semester, more detailed optimizations had to be deferred. Furthermore, the final absolute numbers are not the primary result; rather, it is the comparative evaluation of geometric influences on performance that makes up the value of the simulations. More developed models would likely yield different results, since more precise interaction effects of daylight quality, which is not readily described by bulk UDI values, and window shading would modify design performance, as would further thermal comfort and natural ventilation considerations. Group 01 again improved design performance leading up to the rapid prototyping stage, during which final models were printed with daylight metrics embedded (figure 17).
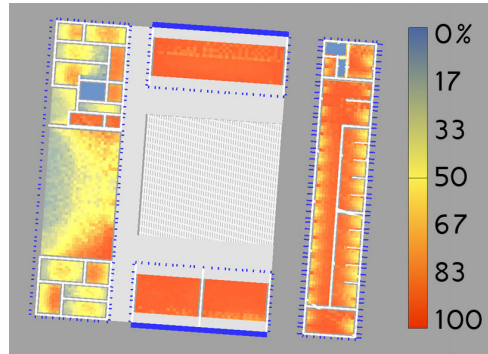

Figure 11
Variant 03 (Florida), Useful Daylight Illuminance, 100 – 2000 lux, % of occ. hours, fins only.
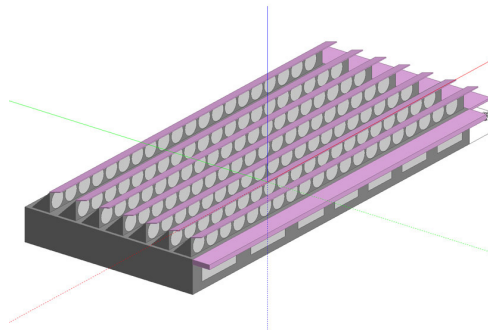

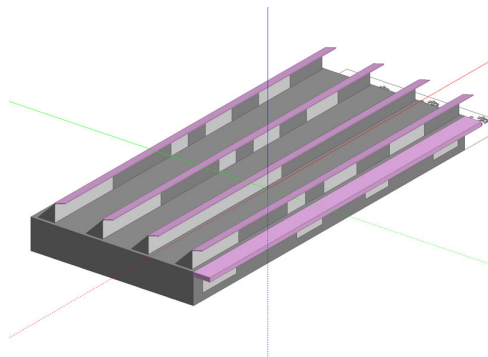Figure 12
DB Model, Variant 01, Iran.

Figure 13
DB Model, Variant 03.

Figure 14
Variant 03 (Iran), UDI 100 –
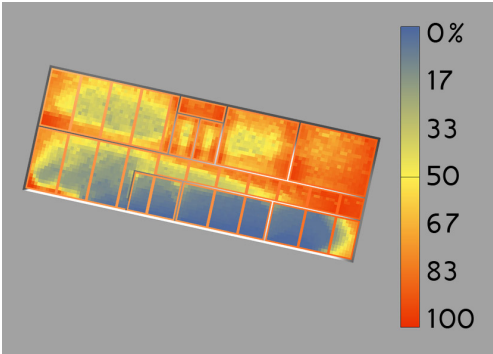2000 lux, % occ. hours, no
shading.

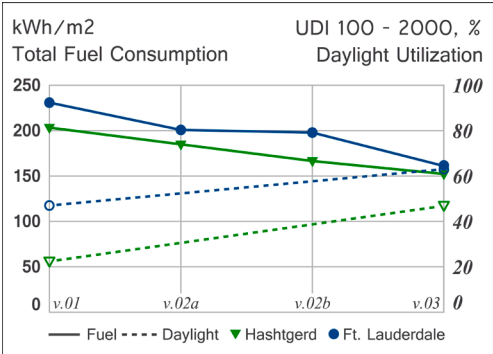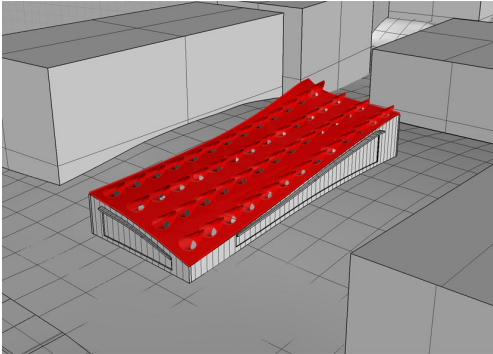Figure 15
Iteration Performances.

Figure 16
Parametric Roof Scoop Geom-
etry of Iran Design.

From a process perspective, workflows that meshed iterative tests with the concurrent exploration of other related but singular design variants appeared as the norm; while we provided extensive instructions on how, in our opinion, to best structure an analysis workflow, the oft-articulated "conflict" between design and engineering thinking came into play, but without inhibiting a measurable decrease in energy demand and a general increase in daylight utilization. Group 02's systematic, iterative approach did not automatically produce a design that performed better than the Florida team's building.

DISCUSSION AND CONCLUSIONS

Most students accomplished a positive interplay of geometry and performance factors. The feasibility of a mixed design-simulation process in achieving efficiency improvements was demonstrated, however it is not only through raw data that such a practice must be evaluated. More than the sum of its parts, it becomes an activity of mediation, complicating both epistemes by collapsing them into the same space of thinking and evaluating. If carefully managed, and to begin answering the first research question, quantitative improvements can be achieved in an integrated manner and through iterative evaluations accompany and even inspire formal experimentation. On the other hand, synergy breakdowns can also occur, experienced by a minority of groups that failed to connect the domain of analysis with the domain of creative production, usually caused by a lack of basic building science knowledge. For if epistemes are to intersect, they need to be at least rudimentary developed, independent of how knowledge is actually produced in science versus design methodologies.

Apart from concerns of principle feasibility, we implied the question of whether a combined design-simulation process would "easily" increase performance. This can only be answered in conjunction with the core question of how design decisions were made in general and specific instances. Since design is often understood as a goal-oriented activity, decisions cannot be evaluated in isolation, but need to

be seen in relation to the perceived whole. Design intent is frequently articulated in a nonlinear and intuitive manner striving towards synthesis by accommodating possibly clashing goals, and thus bears conflict potential with rationalist engineering procedures. Intent encapsulates the always current totality of ideas on how a building should be (N, figure 18), but due to its complexity and intersubjectivity has no holistic representation. It includes all design assumptions, also the ones related to performance, and at any given moment can be understood as a fluent total state of ambivalent interconnections, exemplified by Christopher Alexander's chart of design factor interdependencies (figure 19). Alexander's chart predates the availability of digital design and simulation models, but nonetheless deals with material and social performance interdependencies that form a wicked problem (Rittel and Webber, 1973).

Architects, especially since their separation from manual construction activities (Davis, 2000), have developed a tradition of dealing with problem subset permutations of different domains that still relate to the same object, e.g., how to marry structural requirements with space flow demands. These different subsets are traditionally encoded by a multitude of space-related drawings and models that refer to the same object but are still unique epistemes. As process models, they can act as "machines for thinking" (Smith, 2004) and enable associative artistic leaps. Given that in our case study most projective representations and performance datasets were derived from multiple digital models, strong clues exist that model families may in fact be used by architects within a contemporary continuation of said historic framework, which has been perpetuated by educational design studio practices situated in the lineage of Modernism. Yet since its heyday, developments in simulation and its space-related representation have moved numeric evaluations much closer into architectural planning practice. Still in an apparent conflict with design nature, analysis necessitates clear steps in a rational procedure and relies on steady benchmarks during simulation, oth-
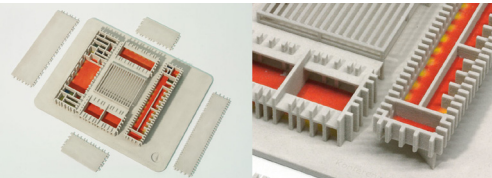

Figure 17
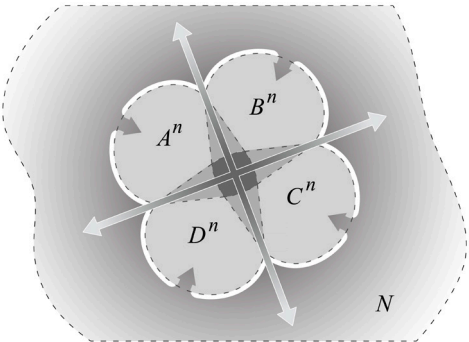Printed Daylight Model, UDI 100 - 2000 embedded, USA Design.

Figure 18
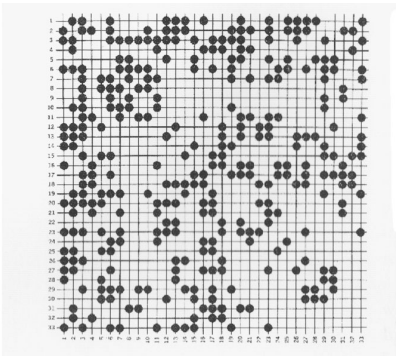Domains of Inquisition / Representation in Design Synthesis.

Figure 19
Field of Design Factor Interdependencies (Chermayeff and Alexander, 1963).

Figure 20
Principle Performance Section: Multivalent Representation, USA.

erwise invalidating comparisons. Yet creative reality is prone to upheavals questioning the very stability of the contained analysis paradigms. How, then, was their interplay managed?

The design observations show that a combination of heuristics, to establish an initial formal seed, and iterative schemes was usually employed, the latter of which predominantly revolved around performance evaluations of building components and were strongly related to prefigured intent; as such, they were encapsulated by and inseparable from the heuristic context. Models that dealt with different design aspects drifted apart, were abstracted to explore isolated performance behaviors and later synchronized with master design models, as shown by group 02. Parametric encoding can be understood as a process analogue to the creation of myriad manual test models and was used to similar design refinement ends. Other groups exhibited related behavior; a multiplicity of independent but related digital models was used to generate analytic, form-related and, most importantly, hybrid or multivalent representations concerned with the form-performance interface and acting as design catalysts. We observed that most beneficial performance decisions were made when students either achieved a parallel presence of design intent across multiple representations belonging to different domains of inquiry, or created multivalent representations that directly combined validated assumptions from multiple domains. To extrapolate a model:

Individual domain-specific types of knowledge (A^n etc., figure 18) are synthesized by utilizing the semiotic flexibility their multivalent representations (e.g. derived from digital models) enable, and thus continuously update global design intent (N, figure 18). In return, the field of intent, newly enriched with additional cross-domain knowledge, permanently influences the originally contributing domains, forming a nonlinear knowledge flow framework that relies less on direct hybridization of design and engineering methods, but instead draws potential from the synergistic possibilities rooted in the multivalence of their respective models' representability.

This model neither invalidates the presence of engineering procedures nor the validity of grown design methods, but in part shifts the discourse onto the level of understanding the mediating role of multivalent representations (e.g. figures 20 & 21), which by virtue of their properties encode quantitative descriptors spatially, relate form to projected performance and should be regarded as articulating one possible state of synthesis among many. The shown sections, daylight plans, radiation images and printed daylight models all partially fulfill these requirements. In a process model that is perceived as a field of possibilities managed by definitions achieved through representations, all contributing domains constantly interact. Representations stimulate processes, can be their result and by feedback effects cause shifts in their respective knowledge source domains; as an example, we found that by running many consecutive simulations, students became increasingly good at without further tests predicting how glazing ratio changes would impact combined thermal and daylighting performance. Yet in order to establish that relationship, it in most cases had to be previously encoded in either conceptual drawings or numerical representations that clearly meshed performance and geometry descriptions. From that perspective, we posit that heuristics and design analysis are complements and enact a process of transforming "tacit" into "explicit" knowledge (Friedman, 2003) of objective performance phenomena that are later used to generate new design seeds through additional representations; if these are then used as active design artefacts, new associative leaps and continuous design synthesis can be achieved.

As a possible consequence for education, designers' knowledge of the contributing domains, especially building science, needs to be improved by linking it with geometry effects through novel teaching formats, as well as research into visual semiotics and their relationship to underlying methodologies combined with the testing of integrated design frameworks. A steady accretion of validated form-performance interfaces allows the concurrent expression of engineering and design epistemes; both need to be acknowledged, regarded in their respective traditions and newly combined to achieve playful precision. Only then will performance increases appear easily from within the design process itself.

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