PARAMETRIC DESIGN: A CASE STUDY IN DESIGN-SIMULATION INTEGRATION

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ABSTRACT

Climate change and rising energy costs necessitate a shift in how buildings that efficiently provide comfort are envisioned. With initiatives now aiming at bringing energy simulation into the mainstream of environmental design, the applicability of state-of-the-art simulations in formally non-constrained creative production needs to be re-evaluated. To this end, a teaching experiment that includes multi-domain simulations as drivers into the early architectural design process has been conducted; Master of Architecture students create a community centre with low energy use and high daylight utilization, presented in case studies. Performance increases are achieved by making appropriate morphological choices only; form and energy are thus linked in a tectonic fashion. A novel design-simulation process model that acknowledges both creative and analytic thinking is derived and discussed in the context of on-going integration attempts.

INTRODUCTION

Building performance simulation (BPS) plays an important role in the conception of energy-efficient, sustainable architecture. Especially its value for early-stage decision-making is commonly expressed (Mahdavi and Lam, 1991), yet studies reveal that the design-responsive use of BPS in practice is far from pervasive (Mahdavi et al., 2003; Venancio et al., 2011a). This is despite the upsurge in demand for numerical design strategy validation, e.g. as expressed by practitioners who desire to improve the knowledge quality of their work processes.

Architects adopt novel design technologies by continuing professional education and the hiring of recent graduates who bring them into practice. To enable this, and to improve research at architecture faculties, numerous initiatives have in the past attempted to anchor BPS in architectural education, often proposing interdisciplinary approaches as one of the overriding concepts to deliver high performance buildings. Yet true integration is only possible if architects also possess sufficient performance domain knowledge to be emancipated actors. In light of this need and the considerable differences in architectural versus engineering modes of decision-making made visible through integration experiments, a shift towards BPS to be performed by architects themselves is currently expressed in academia (Hetherington et al., 2011) and professional guidelines (AIA, 2012).

With the need for sustainability generally recognized in higher education and relatively mature, usable whole-building simulation software available, the question needs to be asked why, despite these efforts, design-intrinsic, robust evaluation tool use in education and professional studios is apparently still rare. Unfortunately, a globally representative study of adoption rates in fundamental architectural education is not currently available; however, if one regards the apparent picture in practice, there emerges a tentative hint that internationally, only a low percentage of schools appears to be consistently pursuing an approach that provides a critical mass of students with design-driven, robust environmental performance evaluation skills. Of course, implicitly linking low professional BPS adoption figures to a perceived global lack of simulation-enabled design teaching is a risky assertion, yet one need only consider the rapid diffusion of other transformative technologies, e.g. Building Information Modelling (Becerik-Gerber et al., 2011), to realize that a willingness to innovate exists and in comparison, BPS still lacks momentum. The potential reasons for this are manifold and also related to the way higher education deals with integration in process and workflow terms.

Architecture is an integrative pursuit that, despite its ultimately physical expression, does not exclusively deal with material matters, but has at its heart social, environmental and procedural concerns mediating the interplay of man and his environment. Examples of the discourse on 21st century teaching curricula make it clear that energy efficiency is an important concern, yet by far not the only issue that needs to be addressed (Gould and Hosey, 2006) and approached from within the studio-driven structure of architectural education. As the studio fundamentally shapes the way students reason, simulation should hence be taught closely tied to it or generally in a "Project-Based Learning" environment (Thomas et al., 1999) that includes a multivariate design problem. BPS performed by architects thus has to be seen in relation to the greater context of production narratives, and consequentially as burdened with inherent limits on how specialized it can become as but one component of environmental design processes; this fact will require a continuing re-evaluation of the role and methods of BPS in architectural education.

In this paper, we discuss our own contribution to the effort of bringing mature BPS into the studio, the building science class "Parametric Design", describe the current curriculum, analyse two exemplary student works and derive an updated procedural model of design-simulation interaction.

CLASS OUTLINE & PRECEDENTS

The BPS class "Parametric Design" has at the time of publication been held for five semesters. It is a stand-alone seminar jointly organized by an EU-funded project that explores new technologies in design and a sustainability-oriented architecture department that currently offers no studio-integrated BPS. The reasons for this include doubts over simulation usability, the feasibility of results analysis to positively impact design decisions and a conflict over what trends should influence creative methods in 21st century studio education. Our initiative is thus designed not only to educate, but to use the class as prototype of a simulation-driven design studio that reflects on the key factors of technical feasibility, process impacts and the nature of simulation influences on resultant building typologies.

Published examples of how studio-centric teaching might integrate BPS exist, either by linking courses to form an integrated whole (Hamza and Horne, 2006), by improving design-engineering interaction (Charles and Thomas, 2009) or as a truly hybrid class (Knudstrup et al., 2009; La Roche, 2012). All agree on the beneficial aspects of exposing performance projections to designers and most present student examples, yet reveal little about how precisely students arrive at individual results by using validated simulation tools. Yet to gain novel workflow insights, it is important to follow design narratives that concurrently expose form and numerical performance indicators; our paper and class are geared towards that end.

As general precedents, stand-alone simulation-only accounts (Strand et al., 2004; Hand and Crawley, 1997) were most useful in reasserting the importance of avoiding tool-led scenarios and to establish a solid building physics foundation. However, our class revolves around a design assignment, the use and learning of simulation tools never isolated from it but accompanying group-specific design processes with increasing scope and accuracy; this is opposed to simulation-only or game-based scenarios (Reinhart et al., 2012) that are limited in capturing the non-linear complexity of design-performance interaction and by default make the architectural problems encountered fully encapsulable by simulation scope, which in real-world design problems is rarely a given.

Curriculum & General Workflow

Our students, mainly at M. Arch. level and usually without any prior exposure to building simulation, are tasked to in the discussed semester create a ca. 800 m^2 community centre featuring low-density offices and multi-use spaces. Figure 1 shows the general class outline; two 2.5 hour sessions are held per week, with individual tutoring available afterwards, which is highly effective due to a good ratio of usually 20 participants and two teachers.

Figure 1 Class Outline

Teams of two chose one location: northern Sweden (Köppen climate classification: Dfc), northern Iran (BSk) or southern Florida (Am), requiring buildings to adapt to local conditions through a unique geometric response. All plots provide real-world context but otherwise allow designs to be freely positioned; neighbouring structures to the South of all sites are minimal in their winter overshadowing impact. The overall class goal is to create structures that through their very fabric respond to site and environment, show a low projected primary energy demand for heating, cooling and lighting and offer high final usable daylight utilization. Whole-building EnergyPlus, via DesignBuilder, and Daysim, through DIVA for Rhino (Jakubiec and Reinhart, 2011) simulations produce all evaluatory metrics. We consider these tools usable by architecture students, since they integrate robust 3d modelling with a well-documented exposure to the underlying simulation engines. Typical design-inclusive classes often rely on Ecotect as main thermal simulation tool (Palme, 2011) due to its "architect-friendly" interface (Attia et al., 2009), but to improve results quality, only extensively validated software is used by us.

Addressing tool usability is only a prerequisite to the more difficult challenge of developing a workflow that meshes design with simulation. Conflicting views at first glance oppose "designerly" modes of evaluative thinking (Venancio et al., 2011b) with structured, hierarchical design phase and linked simulation activity approaches (Bambardekar and Poerschke, 2011). In a class comprised of only architecture students, emphasizing the use of analysis as design driver from the very beginning is desirable, yet would require a-priori skills in applied simulations, which students do not possess. A partially hierarchical structuring of design work and simulation learning is therefore necessary, gradually shifting design decisions, which are initially made in a heuristic and precedent-based fashion, onto a more evidence-based plane, while in parallel increasing simulation scope and complexity as competency improves. Our strategy nudges both domains to converge from two distant poles: design eventually becomes more evidence-based and simulations attain a degree of informed play; both systematic and freely structured activities are thus integrated.

Presentation of simulation and sustainability theory is concentrated in the first half of the semester. As students usually are proficient designers, this allows them to quickly formulate an initial response to the brief, based on rules-of-thumb and case study research. Thermal and daylight simulation are introduced in combination and applied in the weeks before the first presentation, in which two buildings' massing energy model variants plus partial daylight tests are compared and the most promising version chosen. This marks a departure from the methodology presented in an earlier publication (Doelling and Nasrollahi, 2012), which only required thermal simulations after this milestone and caused a lockdown in adaptation flexibility.

Intensive tutoring with interspersed presentations of additional simulation topics shapes the second class half. This phase intensively develops building concepts in a feedback loop of design and simulation, leading up to the final presentation, in which detailed full-building thermal evaluations of predicted primary energy demand and whole-building climate-based daylight utilization are discussed.

METHOD & CASE STUDIES

The strategy students are required to use in order to improve building performance mainly relies on the modification of architectural factors such as facade orientations, wall-to-window ratios and window / building shading with fixed devices or through the structure's form itself. Constructions, HVAC settings and occupancies are fixed throughout the semester (Figure 2), effectively rendering geometric performance strategies into primary formgivers. This simplifies the comparison of different designs, also between climate zones, and leads to adjustments that are robust in their influence, since they do not rely on automated shading control systems or overly optimistic assumptions on inhabitant behaviour.

Main performance decision metrics are the primary energy consumption of the idealized, autosized simple HVAC system, the geometric performance

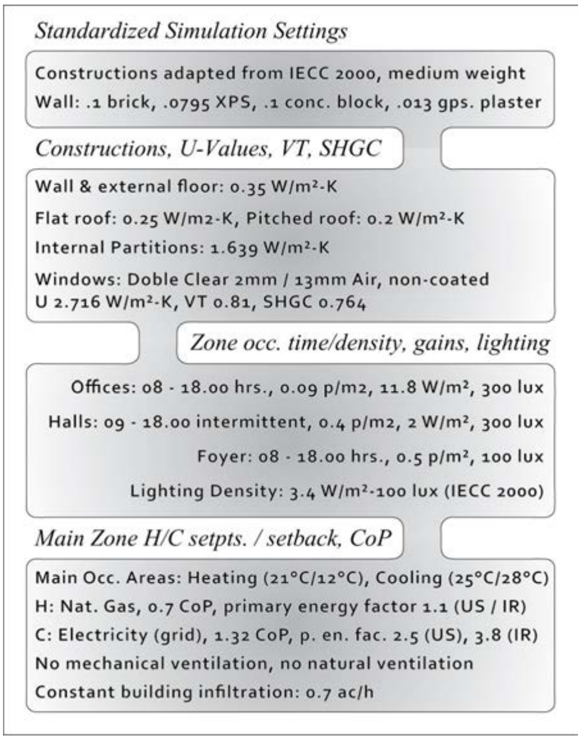

Figure 2 Standardized Settings & Constructions

indicators of seasonal façade solar gains, the climate-based metrics Useful Daylight Illuminance (UDI) 100 - 2000 lux of general spaces with daylight requirement, and the Daylight Availability (DAv) (Reinhart and Wienold, 2010) at 300 lux in offices. Since EnergyPlus' split flux method has difficulty in predicting daylight levels under multiple reflections in a space (Kota and Haberl, 2009), the daylight data furthermore allows an accurate appraisal of light levels and if in conflict with projected lighting energy demand is regarded as more accurate.

Visual and thermal comfort are intermittently evaluated through Evalglare and EnergyPlus, their potential impact on user behaviour discussed and designs modified if severe problems are apparent.

For this study, all simulation models were checked for errors, settings unified and simulations re-run. Due to high tutoring intensity, mistakes are usually caught early; the results presented thus closely correspond to those generated by students.

Design 01: Ft. Lauderdale, Florida, USA

The climate in South Florida is of the tropical monsoon type, with an average annual dry bulb temperature of 25° C and a cumulative annual global horizontal irradiation of 1792 kWh/m^2. Cooling energy use is the main concern, requiring shading of openings while still providing daylight. Group 01's initial form, explored in sketches, separated program elements into distinct volumes and exterior circulation spaces arranged under a shading canopy (Figure 3). First tests with thermal massing and irradiance models determined that the West-facing halls of version A received excessive solar gains and were thus moved completely under the roof, reducing cooling energy consumption by 40 kWh/m^2 as in variant B. Students hence clearly experienced the influence of façade orientation on irradiation intensity. The internal program layout was still tentative and only after this stage began to converge towards the required areas, changing the distribution of internal gains, but nonetheless kept geometric performance impacts measurable. In figures 3 and 4, pie charts show programme area changes.

For variant C, the internal zoning was redeveloped and the facade design iteratively studied in sketches and Daysim simulations. Formal and functional considerations turned the exterior circulation spaces into a fully glazed central distribution hall and internal windows were introduced to light and access spaces from the back, which through added glazing gains to a degree offset the positive thermal impact of the new exterior façade. Solar glazing gains normalized by the occupied area were less than in variant A due to better window placement, but higher than in version B; an improved primary energy demand of 223 kWh/m^2 was still achieved by decreasing lighting energy use, also visible in the UDI 100 – 2000, and by changing the ratio of heating to chiller energy demand. In this phase, the energetic impact of gains localization, changes in materials and fuel type mix became apparent to the designers.

Shading of the hall and yard roof with iteratively daylight-tested lamellas in variant D reduced cooling energy use by 8 kWh/m^2, increasing thermal comfort, yet coincidentally lowered the daylight availability (DAv) in the office spaces to 46%; this is despite raising the UDI 100 - 2000 to 84% by reducing overlit zones in the circulation areas, which limited observed glare and added diffuse daylight. Overall, UDI and DAv were closely coupled to changes in glazing solar gains intensity and localization; DAv suffered most from the additional shading, which was only introduced after studies had projected a higher value with the earlier-implemented facade layout. The increase in underlit areas was thus mainly caused by thermal concerns and highlighted to students the pitfalls of cumulative changes and the difficulty to in tropical climates balance cooling demand with high usable daylight utilization.

Cooling loads were finally lowered by treating the hall and foyer as an unconditioned, naturally ventilated space, showing large savings at a final primary energy demand of 153 kWh/m^2. Interestingly, this marked a hybridization of the first exterior circulation concept with the functional need to offer a more spatially defined, semi-private layout, mediated by the impact of energy use parameters. The accompanying sketch reveals additional design thinking that to raise the roof lamellas could potentially improve ventilation of the enclosed yard; yet such phenomena are, always to the surprise of simulation novices, not modelled in EnergyPlus as behaving functionally identical to real-world air flow.

Group 01 successfully managed the interplay of form and performance and clearly reacted to cross-domain metrics, including their non-linear relationships. The primary energy demand was plausibly related to the daylight analysis results, which additionally helped visualize the location of unwanted solar gains, e.g. in the yard; throughout the design process, students in an experimental and analytic manner developed an increasingly concise understanding of the interaction of solar and interior gains with the building's fabric.

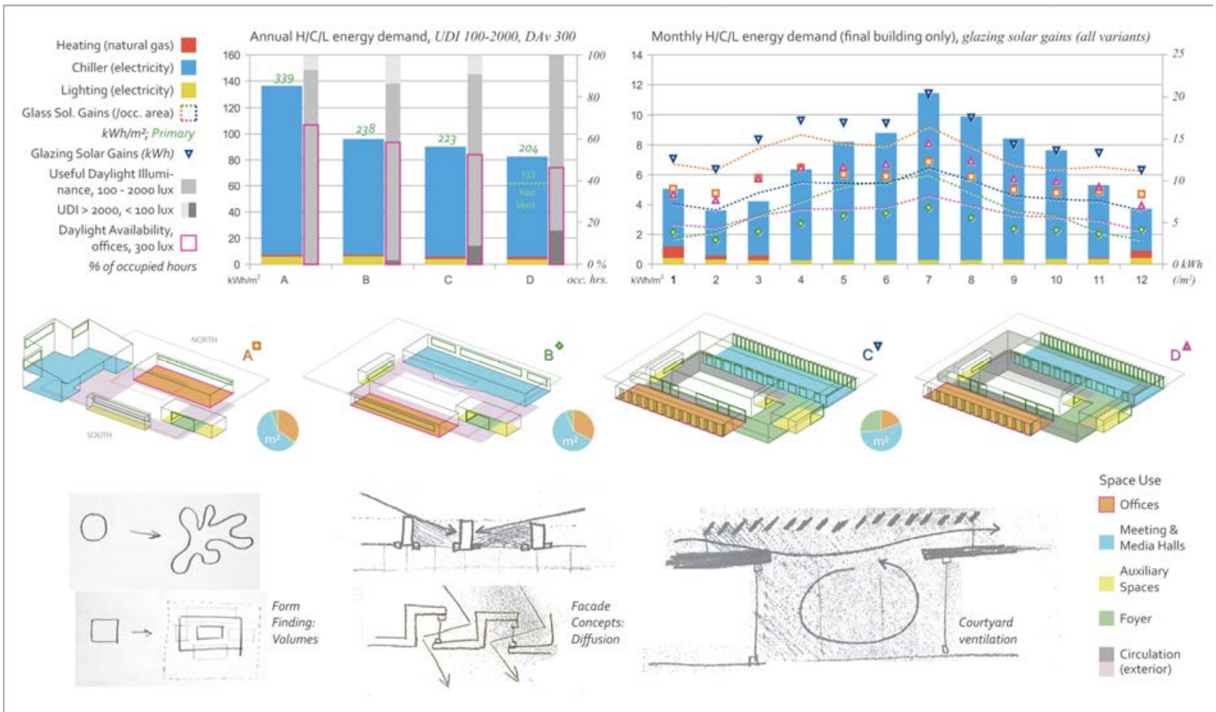

Figure 3 Florida Site Design & Performance Development in all Process Stages

Design 02: Hashtgerd, Iran

The Iran site lies in a semi-arid continental climate; the average annual dry bulb temperature is 15° C, with a cumulative annual global horizontal irradiation of 1951 kWh/m^2. Both heating and cooling demand reduction strategies impact form.

Group 02 decided to answer the site layout with a horizontal block oriented South, intending the orientation to sufficiently mediate seasonal performance and allow winter gains. Program distribution was tentative at first. Variant A did not show good daylight and thermal performance despite the clear massing concept (Figure 4); overly glazed facades minimized DAv and over-pronounced cooling, even more severe in variant B due to the inclusion of a glazed solar chimney, only abstractly modelled and proposed in conjunction with earth pipes; these were excluded from the simulations to focus on geometry. Designers experienced the severity of cooling energy use in a building intended to receive winter solar gains but still overly glazed, and realized that the façade layout plays a significant role in balancing energy use. Perhaps surprisingly, variant B was still chosen due to its site-responsive split-level layout and performance potential through overhangs that were already integrated and offered a better DAv of 20% despite higher glazing gains; the poorer thermal performance was caused by their severity and spatial distribution. Variant C thus saw a re-working of the space layout and solar chimney concept to exclude vertical glazing; overhangs transformed into 1.3m deep external light shelves and the South-facing glass area shrunk, cutting solar gains. Despite savings of 206 kWh/m^2 in primary energy demand, cooling loads still prevailed. DAv of now near-facade office spaces was lacking due to excess light, indicated by the UDI > 2000, and back spaces were still partially underlit, especially during winter blind use to control glare, corresponding with a 0.4 kWh/m^2 increase in lighting energy use.

To again lower primary energy demand and improve visual comfort, the facade was in variant D equipped with deeper overhangs of 2.3m and 1.17m vertical fins, among singular variant tests iteratively evaluated by stepping up dimensions in Daysim and EnergyPlus simulations until an acceptable form-performance interplay was reached. Scale-like skylights with selective performance due to seasonal sun angle variation were added to the roof and South glass reduced to 205 m^2, decreasing thermal discomfort. This stage marked the strengthening of performance domains and the designers' realization of the interplay of multi-domain energy use, user behaviour and comfort; the new facade improved DAv to 60% and overall UDI to 70%, raised heating energy demand but lowered primary energy demand to 161 kWh/m^2 as cooling decreased. A thermally appropriate geometric abstraction of the skylights led to 0.7 kWh/m^2 increase in lighting energy demand; this result is at odds with the daylight analysis and indicates that a more precise modelling of apertures is necessary to check whether EnergyPlus would accurately resolve achieved daylight benefits.

To investigate the initial earth pipe / solar chimney idea, additional simulations were run with scheduled natural ventilation during summer occupancy, but did not radically increase performance due to outside air temperatures higher than the comfort range. This led credence to the concept of considering a coupled system for cooling purposes and to students

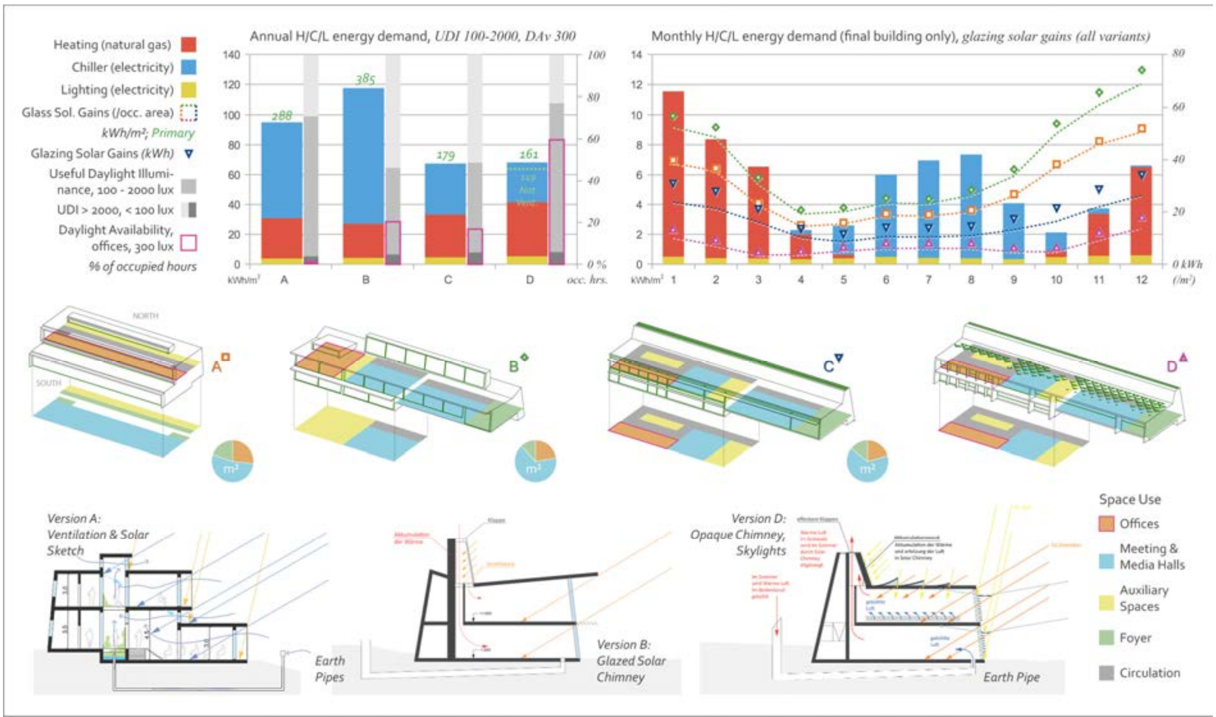

Figure 4 Iran Site Design & Performance Development in all Process Stage

illustrated the limits of simple natural ventilation in climates with high outside daytime temperatures. The detailed sizing of advanced systems goes beyond what would be expected of architectural designers, yet to find energy indications for their possible use is not. Students had initially assumed the chimney to be functionally accounted for in the calculations, while in fact this is not strictly the case. However, they did rightly identify its potential and succeeded even more than group 01 to balance performance domains.

DISCUSSION

Both groups successfully identified individual effects of geometry on performance by using current, validated simulation tools. Significant optimizations were achieved and design intent was enriched, not hindered, by energy use factors; while the buildings are not zero-energy and reveal problems with individual performance factors, these are quantified and addressable. A only gradual development of design parameters and compounded architectural changes increased input uncertainty and rendered evaluation challenging, but well achievable by observing multi-domain metrics; in both designs, climate-based daylight analysis results closely corresponded with thermal observations. Of course, comfort metrics would ideally have to be evaluated to a greater degree, but the resultant typologies offer a good starting point by eventually forming a tectonically robust performance frame. In the multitude of individual learning outcomes experienced, three main insights are most prominent: a) individual architectural elements significantly affect whole-building performance through their geometry, more so than material optimizations; b) in relation to developing design intent, individual elements are modified and evaluated over time to converge to a synthetic solution; and c) at the heart of low-energy design stands the projected well-being of building users, dependent on their behaviour. In a repeating pattern, well-performing class designs generally succeed to navigate these constraints. The dialectic intent of our initiative to investigate learning outcomes, technical feasibility and typology impacts is tentatively resolved by finding that with current tools and didactic methods, designs can even in an introductory class be reliably improved in both energy use and formal terms without overly reducing design complexity. The elephant in the room thus remains process. Integration is often discussed from the separate vantage points of tool use, process research, analysis representation and performance science, while in practice, they are inseparably related. Through a deconstruction of observed design behaviour, we can attempt to identify aspects that bind them together.

A Field of Influences

The case studies show synchronous spatial reasoning, heuristic and iterative performance evaluation evident in a complete-building design process shaped to over time systematically construct holistic performance knowledge. Its properties include:

- Global design intent usually is the design seed generator, not just energy concerns
- Process and performance development are not linear, but both erratic and iterative
- Processes are design-case specific
- Performance and intent interact on all scales, in all design elements and at all times; influence weighting is applied fluently
- A multitude of representations is simultaneously used in design and analysis
- Simulation principles are often not modelled functionally analogous to physical processes

Hence, an integrated process is a dynamic field of related design states and should not be represented linearly; to construct cross-domain knowledge that positively influences design decisions is its goal.

There are differing positions in design research as to the nature of knowledge production; an analysis of objectivist versus constructivist approaches (Feast, 2010) describes the latter as constructing individual knowledge through designerly making, while objectivism is described as systematically converting tacit to explicit knowledge (Friedman, 2003, cited in Feast, 2010), which has a degree of objectivity. Venancio et al. (2011b) argue that knowledge constructed through heuristic simulations enables increased design synthesis by solving dilemmas; our own in-class findings partially echo their results but reveal that if mixed heuristic and systematic simulations are continuously applied in a full-scale design process, quantified multi-domain building performance behaviours emerge, are positively adjusted and persist until the final design stage; that knowledge is then, within its evaluatory scope, objective. Pure design thinking alone thus does not sufficiently capture the cross-disciplinary problem at hand, but is still essential in achieving an accretion of hybrid knowledge states that link objective performance facts with the multi-domain potential of their own changeability, which represents spatio-temporal design reasoning. The class design itself is built on the superposition of both knowledge types. In a previous publication (Doelling and Nasrollahi, 2012), we were only tentatively aware of this fact and constructed a process model that posited design-performance representations as enabling synthesis. This allowed us to evade the black box of design model cognition, but through further results analysis and continuing work of our peers, we feel confident to calibrate our earlier model one step further.

A Model of Models

Design and analysis have evolved production modes towards encoding process states in digital models that allow a multitude of possible expressions. These are

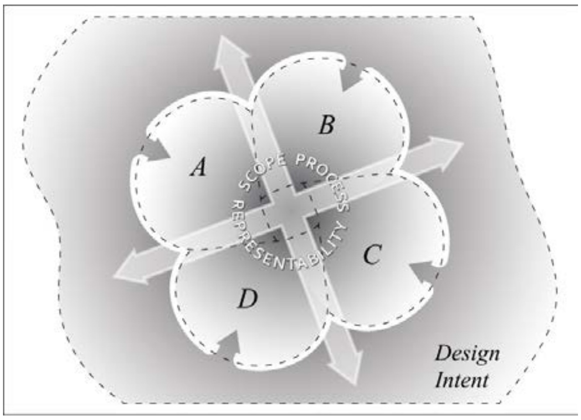

Figure 5 Multi-Domain Knowledge Synthesis

encoded extensions of knowledge, exist regardless of the nature of workflows that led to their creation, but belong to different epistemological domains (A - D, Figure 5), e.g. design and engineering. Global design intent is intersubjectively constructed and encapsulates individuals' knowledge of different domains; as experienced in the case studies, it is adjusted on a per-project basis by multi-scale, multi-temporal domain interaction and continuously feeds back to update source domains. Synthesis of design and performance information is achieved by in strategic moments overlapping model states that offer a comparative interface, which may happen entirely in the mind of the designer but can be aided by deriving multivalent representations that show performance indicators correctly linked to their causative spatial factors. These representations then act as manipulable proxies of the underlying cognitive models. When synthesizing multi-domain information to expose the properties of a design state, it is important not to construct domain relationships that can be expressed, e.g. in text or images, but in fact fail to capture a physically probable performance outcome. For example, overly optimistic architectural renderings, if taken at face value and understood as simplified simulations, often fail to predict daylight performance. Therefore, several checks exist in the process model; the mediating variable "representability", with others encircling the synthesis area in Figure 5, assures that no illegal representations as above are derived and comparisons are semiotically valid. "Process" controls that synthesis checks are made at the right time in relation to design intent and other domains (e.g., to consider thermal impacts of added daylight). "Scope" applies to how simulation and model principles operate in contrast to real-life phenomena, as seen in the case-study natural ventilation example, in which effects were assumed present in simulation that are not part of the solver. To consider scope means to check that no states or representations are synthesized whose functional assumptions are incompatible. This is key, since if domains agree in process and representability but refer to realities insufficiently or incompatibly covered by the methods used to evaluate them, invalid assumptions are the result and a minimum workable overlap needs to be discovered instead.

CONCLUSION

The outlined model is not intended as an abstract exercise, but offers tangible benefits by evaluating tool use, analysis/design representations and base simulation principles in their combined potential to deliver synergy by means of their very properties intended to do so. Through the model's lens, tools that allow high-level, complex knowledge to be flexibly encoded and output through, e.g., space-based metrics, generated by engines with high physical analogousness to real phenomena, would be ideal. The model also unburdens design processes from constant rational analysis demands; it does not matter how precisely a design process is organized as long as it is able to provide knowledge states that are at regular decision points relatable to performance domains. This is not to say that strategy itself does not matter; the method of optimizing energy demand through form is itself an example of a process type adjusted to allow greater ease of domain overlap by tectonically linking optimizations with spatial parameters. As evident in the case-studies, individual design processes are unique, regardless of overall strategy; a distinction needs therefore to be made between strategy and process flow, which are not synonymous. The focus on finding overly prescriptive design-analysis hierarchies does, in the authors' opinion, fundamentally stifle integration attempts, alienates architects by ignoring their field's rich process tradition and is in part responsible for integration failures as alluded to in the introduction. We also experimented with overly normative work instructions, only to have them literally tossed before our feets by designers; adopting the new model has in an applied fashion enabled us to restructure tutoring and class design to provide better results. It shifts attention away from an overthinking of sub-issues to instead ask the question of how they are mutually contributive and acknowledges both complexity and specificity, which in their interplay are all too often ignored; to communicate the potential integration of BPS without disrupting design thinking is essential to gain increasing professional and academic support.

In architectural design, early-stage unstructured information is routinely dealt with in a synthetic manner, from the outset shapes design intent and is used to gauge the social and behavioural impacts of space, which gives BPS performed by designers great future potential. It is hoped that renewed experiments with design-driven simulation will lead to a rethinking of how complexity can be managed by making knowledge intersections and their enabling carriers more transparent, instead of relying on normative oversimplifications. Our own experiences and those of our peers reveal that there is great potential in this, with limits constantly shifting and only constrained by actors' willingness to innovate.

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