GEOMETRIC COMPLEXITY AND ENERGY SIMULATION

Evolving Performance Driven Architectural Form

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Abstract. The research presents the custom development of a software tool and design process for integrating three design domains, their respective objectives, and geometric parameterizations. It then describes a set of experimental projects and analyses in the context of informing form and geometric complexity. Preliminary results of the multidisciplinary design optimization prototype, which, implements a genetic algorithm, are then presented. The findings include discussion of the value for architects for designing-in performance e.g. the bringing of the energy simulation and financial pro-forma upstream in the design process and of the value for trade off design decision making the system provides. The summary discussion includes the benefit of breeding architecturally complex geometries and the kinds of optimisations or search for improvements on designs that can be achieved.

Keywords. Parametric; generative; optimisation; design decision support.

1. Introduction and Motivation

Our research looks to the notion of informing form in the context of heightened awareness and necessity for performance in architecture, urbanism, and building systems. As a foundational mind set, the research builds upon associative parametric design methodology, as a solution space approach incorporating multiple design domains and criteria. The method and technology presented enables an expansive creation of design solutions sorted, bred, and optimised to meet the demands of architectural human computer interaction- the design act- and the oft-competing design objectives. Given our architecturally centric approach, the limitations of design cycle times and project complexity become less of a barrier and yet the problem of solution ranking and qualification become paramount. The
research builds upon earlier design integration research and acknowledges the necessity of domain specialization and expertise. The research presented here stems from a focus on early stage design decision making and the desire to inform these early design decisions with rapid and more accurate performance e.g. energy awareness specifically for architects. At the intersection of energy simulation with design geometry and process the work looks to improving upon our empirical understanding of environmental impact while protecting and supporting architectural ingenuity and its geometric complexity. While current modes of practice do include energy simulation, generally it is inconsistent or sporadic and rather implemented post facto with respect to the analysis of architectural geometry and form (Crawley et al., 2008; Schlueter and Thesseling, 2009). It is with the advancement of parametric design technologies and algorithmic search techniques that the research focuses on the abilities to rapidly generate and explore design options. Design exploration is at the core of the research where design is understood to be multi-objective and requisite of designer driven logical structures and choice (Ren et al., 2011). Fundamentally, the research addresses the challenge that design complexity is no longer solely the geometry itself but how to incorporate performance feedback into design decision-making process.

2. Background and Review

At the outset for the research contemporary design process faces pervasive and deep-rooted limitations with respect to incorporating and more so correlating energy simulation with complex geometry. These limitations are in some part related to tools and interoperability, domain knowledge integration (Malkawi, 2005), and design cognition and complexity all of which contribute to design uncertainty, waste and design cycle latency. Our work is situated through four primary precedent categories; parametric design and design exploration; performance simulation and feedback; multidisciplinary design optimization (MDO); and evolutionary design techniques. Intrinsic to our interest, the research acknowledges design process as being inherently complex, and one that requires iteration and exploration (Eastman, 1970). As one begins to add energy simulation and other performance criteria earlier into the design process the complexity compounds for the designer to manage.

2.1. PARAMETRIC DESIGN AND DESIGN EXPLORATION

A fundamental building block for our research is the use of parametric design and modelling for rapid design iteration (Gero, 1990). Furthermore parametric design thinking and modelling enables relational i.e. correlative, integral and explorative
design process (Menges, 2011). Important to the research is the understanding that iteration can increase the possibility for finding higher performance designs through the notion of design exploration of both geometric and their non-geometric variables according to established design objectives and constraints (Shea et al., 2005). One recent precedent utilized the parametric form generation process to find various performance envelopes and demonstrated promising capability to support design decision making.

2.2. PERFORMANCE SIMULATION AND FEEDBACK

While constructability is often the first issue to be tackled by designers in developing complex geometry (Glymph et al., 2004) our focus along with others is to append this obvious need with that of informing these forms with performance criteria such as energy use intensity, project economics or environmental footprint. This is especially important in the early design stage where the decision made has a significant impact on the life-cycle cost of buildings (USGBC, 2003). The use of performance simulation is not a novelty to the field of architecture, but previous studies show that performance-based analysis methods conventionally adopted rarely are able to support these early stage design decisions due to time limitation. Augenbroe summarises current needs of the building simulation tools and concludes our focus should be on: 1) rapid evaluation of alternative designs; 2) tools to support decision making process; and 3) improving designers ability to solve nonlinear and multi-criteria problems (Augenbroe, 2002). Recent efforts to improve the integration of the design process and the energy performance domain include: combining a parametric design environment with a spread sheet calculator to provide real time performance feedback (Sanguinetti et al., 2010); and the ParaGen project, which explored a performance based design process by combining parametric modelling and genetic algorithms correlating structural performance and solar energy (Turrin et al., 2011). Yi and Malkawi developed a method to apply energy performance feedback to complex geometry by defining hierarchical relationship between geometry points (Yi and Malkawi, 2009). Other recent works have focused on the early stages of building design to fulfil energy performance requirements through parametric definitions (Toth et al., 2011).

2.3. MULTIDISCIPLINARY DESIGN OPTIMIZATION (MDO)

Multidisciplinary design optimisation (MDO) refers to optimisation methods used to solve design problems with multiple objective functions and that incorporate a range of disciplines (Coello Coello et al., 2007). As defined by Poloni, MDO is “the art of finding the best compromise” (Poloni and Pediroda, 1997). One precedent
investigates the application of a multi-objective genetic algorithm (MOGA) for finding the optimal in the trade-offs between capital expenditure, operation cost and occupant thermal comfort in building design. Others tested MDO in a building design setting with thermal, structural, financial and environmental performance evaluation by integrating all the platforms via an IFC scheme (Geyer, 2009). Magnier uses the approach to optimize the energy consumption and thermal comfort of a residential building (Magnier and Haghighat, 2010). The “CATBOT” project utilized MDO to link complex geometry to structural analysis (Keough and Benjamin, 2010).

2.4. EVOLUTIONARY DESIGN TECHNIQUES

The invention of evolutionary algorithms can be traced to the work of John Holland (Holland, 1992) and genetic algorithms (GA) to Goldberg’s work (Goldberg, 1989). The development of an influential evolutionary architectural theory and application of GA and evolutionary process on complex geometry is that of John Frazer’s work (Frazer, 1995). Another seminal application of GA to design research and environmental performance for multi-objective design problems is that of John Gero; critical to note is his use of Pareto optimisation to enable design decision making (Gero et al., 1983). Recent example of environmental applications of GA to multi-objective design optimization problems include the integration of CFD analysis and the coupling of indoor comfort factors to external climate (Huang et al., 2012) along with an investigation into the practicality of design applications that used evolutionary algorithms to generate and filter design options (Krish, 2011). Our research builds upon the use of GA for design optimisation to search for a set of better-fit solutions in which a synthetic trade off decision must be made by the human designer or team.

3. The Prototype the ‘H.D.S Beagle’

H.D.S. Beagle (the Beagle) integrates the three design objectives through an integrated and evolutionary process. The three objectives of interest in this research are energy, financial and spatial programing compliance performance. The selected respective performance measurements are energy use intensity (EUI), net present value (NPV), and spatial programing compliance score (SPC). In order to support the form generation in concert with these three performance feedback in a semi-automated -directed search- there are three key activities that comprise the Beagle; 1) initialising the model through parameterisation; 2) integrating the domain specific analysis engines; and 3) the automation of the generation of evolved i.e. improving design variants through the genetic algorithmic search and
Pareto optimisation. The full description of the tool and tool development is in our previous publication (Gerber and Lin, 2012).

4. Experiments and Analysis

The research team has developed 14 cases to date to test the Beagle from simple to complex geometries. The intent was to explore surface geometry in terms of the ambiguity i.e. designer uncertainty as they relate to energy use intensity. A summary of this spectrum can be observed in Figure 1. All results are then analysed via empirical measurements across scenarios but also via process map comparisons in order provide more certain understandings of the performance characteristics of a particular complex geometry. By counting the number of offspring and generations and then comparing surface count of each scenario’s initial energy model to time we plotted the design cycle latency effect, as illustrated in

Figure 1. The graph illustrates the relationship between geometry surface count and energy analysis time. A sampling of the scenarios and their offspring counts are overlaid on the graph. The 3D images are the visualisations of each scenario’s tessellated energy model.
Figure 2. There are various factors that impact the energy analysis time, such as the time needed for the translation of a geometric model into an energy model or to provide said energy model to the GBS for analysis as well as Internet stability. Conventional energy simulation software and methodology rarely support a designer’s interest in scale of the possible design exploration and in particular the impact of overall geometric form coupled with the multiple objectives. As a result, in order to observe the potential benefit to include form exploration in the process, four variations of scenario 14 (Figure 2) are tested by exploring the same energy parameters and project requirements. Climate data and site related information is provided by the same hypothetical site. These four models are designed as a mixed used building to fulfil the requirement of 11,000 sqft retail space, 20,000 sqft office space and 10,000 sqft hotel space. The three explored energy related parameters are: 1) “Target Percentage Glazing” ranging from 20%~80%; 2) “Shade Depth” ranging from 0~3ft (0~0.9m); 3) “Target Percentage Skylights” ranging from 0%~60%. The results show the benchmark energy performance for model (a) is 145 kBtu/ft²/yr (457kWh/m²/yr). The solution space range for model (a) when varying the 3 parameters is 101~236 kBtu/ft²/yr (319~744kWh/m²/yr). Then we compared the case of model (a) including geometric variation, illustrating the exploration of building form, better energy performance as a minimised EUI ranging from 46~132 kBtu/ft²/yr (145~416 kWh/m²/yr) is found. Next, we increased the complexity of the building geometry to measure if the performance will improve. In model (b) we add the scale factor on top of the building footprint; in model (c) we add another scale factor in the middle of the building footprint; lastly, in model (d) we add the rotation parameter to explore even more complex geometry. From the results in Figure 2 we find model (d) provides solutions with better energy performance through the EUI values. Model (d) also provides better financial and design scores solutions when compared to the first three model settings. Figure 3 model (d) has the most complex geometry including double curvatures but as well seems to provide a higher performing solution space when the Beagle is run resulting in a range of 44~209 kBtu/ft²/yr (139~659 kWh/m²/yr). It should be noted that current financial model does not reflect the additional structural cost from the increase of geometric complexity. However, the current experiment does demonstrate that our searching method and form exploration provide opportunities to finding better performance solutions.

In order to evaluate process improvement of the Beagle four different process maps are summarized according to our current experimental, pedagogy and case based experiments, as shown in Figure 3. For the four process maps, we specifically use five categories to evaluate the Beagle process improvement: 1) time required to generate a design model; 2) time required to generate an energy model; 3) time required to obtain the analysis feedback; 4) numbers of options to support
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(a) Initial Performance
- **EUI**: 145.0
- **NPV**: 11,111
- **Design**: 26.8

(b) Solution Space
- **EUI**: 45.5 - 131.5
- **NPV**: -11,11 - 374.8
- **Design**: 58.2

(c) Initial Performance
- **EUI**: 91.0
- **NPV**: 81,111
- **Design**: 87.2

(d) Solution Space
- **EUI**: 43.9 - 85.5
- **NPV**: -25,500 - 724.6
- **Design**: 28.6

Figure 2. The table illustrates the improvements found in the energy performance feedback for scenario 14 as they relate to model geometric complexity.

decision making within a specific amount of time; 5) the ability to help solve the multi-objective problem. The results can be seen in Figure 3.

The first two processes are summarised from a case-based experiment, which highlighted the interoperability issues between design domain tool and energy simulation tool. In these two processes, the designer or the engineers have to create different model for energy simulation purpose. If any geometry changed, the energy model needs to be manually adjusted accordingly due to lack of parametric definition. In the first process map the time required to get the performance feedback is the longest (168 hours) and by the time the designer obtains the feedback result, the initial building form has been decided. Therefore the feedback can only have limited impact for the overall building geometry. The second process illustrates a more rapid feedback 6-hour cycle, however, is still not sufficient to
support design decision-making. The third is a process map summarized from a pedagogical experiment. The results suggest an increase in design feedback compared to the first two processes. This pedagogical experiment also observed the limit of human cognitive load when it comes to complex geometry and performance criteria i.e. problem scale and coupling. In our experiment, students were asked to design explore by varying 9 parameters; 5 driving the geometry with the other 4 being energy related. The objectives as with all scenarios are to minimize EUI, maximize NPV and maximize SPC. However, the observed variety in novice exploration processes provided limited feedback to support decision-making.

We then compared these process maps and the pool of models to the Beagle process – process 4 in Figure 3. By comparison, through the selection of best fit individuals from each generation to provide the basis for the next generation, the Beagle provides more design options as well as improved EUI, NPV and SPC.

Figure 3. The four process map comparisons of energy simulation feedback and overall process improvements of the incorporation and correlation of complex geometry.
5. Conclusion and Discussion

The research illustrates an increase in a designers’ ability to foresee the performance behaviours and therefore enhance architectural geometric complexity critical to being in step with contemporary energy use intensity demands. Our current findings suggest that the Beagle consistently evolved offspring towards more optimal solutions; where energy performance is improved by up to 50% sometimes and yielding highly non-intuitive but architecturally interesting forms. The affordances that the research empirically document include the increase in size of solution space and possible better fit solutions; the speed in which designs are generatively and rapidly iterated upon in terms of evaluation; the addressable scale of the problem i.e. our ability to tackle complex formal analysis; and the simultaneous visualization of the design criteria and the their trade-offs. What the research most successfully seems to suggest is that project objectives such as geometric complexity when coupled with energy simulation are best understood through an MDO supported design process. Otherwise designers cannot manage the complexity cognitively and will not be given the chance to optimise while in geometry generation stages. Fundamentally the Beagle provides the performance feedback irrespective of this geometric complexity, it is agnostic to the amount of surfaces or topology.

References


