Performance-based Design: Current Practices and Research Issues

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In view of current developments in the theory and technology of digital design, potential novel directions for environments that support performance-based design are beginning to emerge. The field of performance-based design is defined through an analysis of current work in the field. Various models of performance-based architectural design are presented and discussed. On the basis of this analysis, key concepts and issues in the application of performance-based design in architecture are defined and certain research directions for the development of new approaches are presented. Finally we propose a new approach termed: Performative Design. Performative Design suggests that in creating simulation environments for performance-based architectural design both generative and evaluative capabilities can be integrated within performance-based simulations. The potential of performance-based simulation as a model of performance-based design is explored through a case study from an experimental digital design studio. Implication of this work on future research directions in the field is explicated.
I. INTRODUCTION

1.1 What is performative?

The term performative may represent a synthesis of two of the essential characteristics of digital design. Digital design processes support transformation and generation of a geometrical model and they support analytical evaluation of environmental performance based upon simulating physical conditions such as solar or structural loadings. It is the potential of an integration of evaluative simulation processes with digital ‘form generation’ and ‘form modification’ models that is implied by the term Performative Design. The term further implies that performance can in itself become a determinant and method for the creation of architectural form. In such circumstances digital design diverges from a design paradigm in which the formal manipulative skills and preferences of the human designer externally control the process to one in which the design is informed by internal evaluative and simulation processes. Under such a definition of digital architectural design as an integration of evaluation processes with digital processes of form generation and/or modification, various theoretical assumptions are presented.

Well-known applications of evaluative environments in CAAD techniques have been employed in architectural and engineering practice since the Seventies. Until today most of such applications are aposteriori. That is, they require a well-defined geometrical and physical frameworks in order to be applied. Performative morphogenesis as a theory produces a transition from a design paradigm of “form making” to one of “form finding” [1]. Thus digital design in general, and performative-morphogenesis in particular, also promise the ability to find form, or to obtain unexpected and even unique solutions. How, and to what extent, the human designer is involved judgmentally in interaction with such media is a further research aspect of form-finding techniques. How the design model can incorporate at an early stage of design both a geometric framework and other factors such as structure and material are also essential questions towards the definition of performative-morphogenesis.

Digital design systems in architectural applications contain three components that in their integration support design:

- the geometric model is formulated in such a manner that it is capable of transformation and generation according to input of evaluation processes;
- the evaluative processes can be integrated with the geometric model and thus produce modification/generation processes in the geometric model; these may be single criteria evaluations (e.g. structural performance, solar loading, acoustic performance) or, multi-criteria evaluations including multiple performance and optimization factors;
the system provides for the interactivity of the designer as a moderator of the various processes involved and/or as a designer of algorithmic models for form generation and/or modifications.

The integration of these three components can be employed as a means to identify the current state of the art. In the past decade, the design of many significant architectural projects has been strongly influenced by computational performance simulations exploited in their form-finding processes. This has almost universally been the case with respect to various forms of structural and environmental analysis through which the engineering contribution to architectural design has become a both a characteristic of digital design and a component of all advanced architectural projects. Thus it can be stated that the methodological and technological prerequisites for form-finding in architectural design are beginning to emerge. One of the main objectives of this paper are to trace and define certain of these practices; and to define key concepts and research issues for the potential advancement of the field. Following this research survey and theoretical introduction to the field, the potential for the advancement of this area of digital architectural design currently requires both a clarification of its theoretical foundations as well as advancement of research into the relevant design technologies and techniques. Building upon the many significant, though partial, achievements of the past decade, this research provides a road-map for future advances towards performance-based design. Finally, an experimental approach of Performative Design generation is presented.

2. Performance – based design

2.1 Introduction

Performance-based design may be generally considered an approach in which building performance becomes the guiding factor in design. Performance-based models in architecture may be defined as the exploitation of building performance simulation for the modification of geometrical form towards the objective of optimizing a candidate design. Design performance has long been recognized as an important issue in architectural design, and has long been considered a seminal component in the value-system of architectural design. Methods and techniques known as “appraisal aids” that were developed at ABACUS during the early days of CAD [3,4] have been currently presented as pioneering works that still present important insights for contemporary work [5,6].

Contemporary approaches to performance-based design are fundamentally different from conventional CAD simulation processes. Traditional simulation tools are premised upon the ability to simulate and evaluate performance of the object itself once it has been defined at an appropriate and desired level of resolution. Thus they are rarely employed in
early conceptual stages of design. Current technologies are, in general, not capable of the integration of design synthesis formation processes that are directly informed by performance-based simulations. Therefore most current systems are not morphogenetic. It is the human designer who adapts the geometric design model in order to accommodate optimized and evaluative findings.

A typical simulation process can illustrate this distinction. A frequently applied simulation method that characterizes testing and evaluation in conventional structural design processes is the Finite Elements Method (FEM). This type of simulation requires a well-defined model. Only after analyzing the structural stability the design is re-generated. In conventional design model, evaluations provide feedback for iterative design modifications. Future directions for performance-based design can provide digital model that couple principles of performance with principles of generation [7]. Here modifications of the model can be automatically achieved by generative processes controlled by the analytical and numeric findings. Performance-based design is redefined as the ability to directly manipulate the geometric properties of a digital model on the basis of performative analyses in order to optimize performance. Instead of analyzing the performance of a design, and modifying it accordingly, ultimately it may be possible to directly inform, generate and modify the design model using performance-based simulations.

In the following section current advances in performance-based architectural design are presented and certain key concepts and enabling technologies are identified. This review of current architectural design practices and advances in digital environments enables us in section 3 to define certain of the key concepts related to theoretical and methodological foundations of future developments in the field.

2.2 Performance-based architectural design: advances and contributions in current practice

Within the past decade a range of projects has been developed that have exploited emerging digital technologies that are directly or indirectly related to performance-based design. These projects are by now well-known and have been extensively published and analyzed in the professional and scientific literature. A number of these works is selected in order to identify how they as a group of precedents have achieved significant contributions to the field of performance-based design. The projects themselves range over case studies in which digital environmental performance analysis techniques are the major focus of the work; in which design modeling (particularly the interpretation of “parametric design” as an approach) is the focus; and include iconic projects integrating both environmental analysis and parametric modeling. The majority of important contributions to the advancement of performance-based design have emerged in projects in
which there has been a coalescence of these factors. In most of these works environmental performance simulations have been employed in parallel with associative modeling and parametric design in order to optimize performance.

Many designs associated today with digital architecture reflect a new awareness of performance-based design [6,7]. Recent projects that have incorporated simulation methods in the design process are now well-known [5]. They include among others: the Greater London Authority Headquarters, (2002) and the Swiss RE building (2004) designed by Foster & Partners and Arup Associates, the ZED project by Future Systems (1995); the Kunsthuis in Graz by Peter Cook, Colin Fournier; Bollinger and Grohmann, (2000-2003) [8].

One fundamental ingredient in the advancement of work in the field has been the existence of parametric modeling systems. Associative geometry in parametric design enables the establishment of a schema of dependencies, or co-dependencies, of the elements of geometric models and thus controls the behavior of such objects under transformations maintaining topological characteristics. Among the classic studies of parametric design is the variable truss design of Grimshaw’s International Terminal at Waterloo Station that exemplified this “dynamic” potential of parametric design [2]. Potentially performance-evaluation can inform parametric model and modify the geometrical model, leading to performance-based generative processes. One of the key attributes of parametric modeling techniques that is essential to performance-base design is what Burry calls the “meta-design”, or the parametrically variable model [9]. A “Meta-design” approach supports transformations. Burry’s now classic work on the digital formulation of the geometry of the Sagrada Familia Cathedral of Gaudi exploits these design transformational capabilities of parametric modelers. In his studies of the Rose Window of the Passion Façade the associative geometry schema controls the process of parametric modification. Algorithmic control of the processes of parametric variations is one of the methodological cornerstones of future performance-based systems, since it may potentially be exploited as a technique for the modification of the meta-model under conditions of finding a performatively optimal solution. Thus, in Burry’s terms, the meta-design, or more exactly, the meta-model contains a schema of associative geometry supporting topological transformation of the geometrical model.

The design process of the Swiss Re building in London is an iconic case study of a performance-based approach including parametric design controlled by interactive process towards optimization of performance, in this case, the building profile and the skin were modified according to structural performance and wind loadings. Swiss Re has a well-documented design process and illustrates many of the important methodological contributions of such digital environments. In discussing refinement of the design process in the parametric design environment, Aish employed the
term “living model” [10] to describe the interactive potential of working in a parametric design environment with associative geometry (Generative Components which was used in Swiss Re). In such environments, the ordering and dependencies of parametric modifications can be defined by the dependency relationships. With respect to advances of parametric design as a foundation of future performative systems the body of work of Whitehead and the Specialist Modelling Group at Foster and Partners (including Swiss Re, the Courtyard Roof of the British Museum and the London City Hall) as explicated by Whitehead [11,2,] and Aish [13,14] bring us to the cutting edge of the potential and limits of this approach to the integration of evaluation and design synthesis. To complete the picture of those achievements it is necessary to credit the work of these designers as members of the Smart Geometries Group (SG) which has further promoted the technologies, design methods and educational potential of the approach.

We have observed that the cutting edge of current systems development lies at the point of how and by what techniques the parametric model of a design is modified by evaluative analyses and optimization techniques. Beyond this there is a body of theoretical and methodological issues related to the potential of integrating computational approaches to design generation. Primarily the concept of morphogenesis is the key for supporting form generation by performance.

Generative systems such as grammars [15,16] and genetic algorithms [17] are well known in the scientific literature, however, their applications in architectural systems and in performance-based systems in particular have been few. A brief discussion of one of the recent successful applications of a generative approach to performance-based architecture will serve to clarify the potential and current limitations of such systems. A generative method has been developed by Kristina Shea [7,18]. The EifForm system was developed in the domain of structural engineering to design long-span roof systems. The system can currently generate planar trusses and single layer space trusses. In its operation it attempts to demonstrate the synergies between associative modeling and generative systems which can potentially lead towards integrated performance-based generative design tools. The system is designed to provide for different spans, diverse geometric conditions of site, and to produce either homogeneous or heterogeneous geometric solutions. The design process of the EifForm system includes a recursive design cycle including generation, evaluation and modification stages. It can accommodate performative factors such as diverse loadings and materials. The performance model provides analysis and evaluation that includes structural analysis and stochastic optimization to support optimally directed exploration of discrete structural forms in relation to performance. The generative method employs structural shape annealing which integrates grammatically controlled parametric shape generation.
A parametric system and associative geometry modeler was developed in Generative Components employing a graph-based associative geometry modeler. Modification of parameters after the first iteration (of generate and test) is still accomplished by the human designer. However, generative systems have limitations with respect to their application in architectural problems, in general. Since generative systems require a strong formalism for propagation they do not necessarily accommodate a large range of architectural problem areas. Shape Grammars [15] are perhaps an exceptional case, since they have been widely applied to architectural design particularly with respect to problems related to configurative descriptions. Generative systems are an essential part of the future development of performative architectural systems, however, they are still at stage of development.

3. Key concepts and research issues in performance-based architectural design

This review of the state of the art in performance-based design in architecture has produced a conceptual framework for reformulating current research questions. Related concepts are presented below:

3.1 Topological models in architectural design

Performance-based systems in architecture have been demonstrated to be dependent upon the form and technology of the models behind the systems. What has been referred to previously as Burry's meta-model is a topological model that maintains fundamental dependency relations constant while enabling the properties of transformations. This ability to give primacy to the structure of relationships and qualities that exist in the context of architectural problems makes topological modeling techniques one of the imperative component of performative architecture. Since traditional modeling in architecture tends to be typological in nature, new approaches to the modeling of architectural systems and problem structures are required.

3.2 Parametric design and associative modeling

The reconsideration of topology and non-Euclidean geometry as a methodological basis for digital design has contributed to the exploration of new geometrical possibilities. Within this emerging context of computational geometry in architectural design, parametric and associative models are powerful tools for design. In such a context, the topological effect of digital environments enable the reconfiguration of parameters of a geometrical structure [19,20]. This attribute of parametric geometrical variability has strongly contributed to the symbiotic relationships between parametric design and performance-based design.
In parametric design, relationships between objects are explicitly described, establishing interdependencies between the various objects. Variations, once generated, can be easily transformed and manipulated by activating these attributes. Different value assignments can generate multiple variations while maintaining essential conditions of the topological relationships. Technologies of associative parametric media (Generative Components, Digital Project, and others) today provide design environments in which the designer can define the generic properties of a geometrical structure within a user-defined framework.

3.3 Interactive design in performance-based design

These technologies have opened up a universe of possibilities. The static coordinates of shapes and forms of conventional digital media are replaced by computationally dynamic constructs of topological models. This combination of interactivity and parametric transformability controls perturbations that generate discrete structural variations within design formation processes. The body of theoretical concepts related to parametric formations includes adaptability and change, continuity, proximity, and connectivity.

The term versioning suggests that the design is an evolving differential data-design entity [21]. Versioning is an operative term meant to describe design variations. It refers to topological form variations rather than traditional form-composition (e.g., form repetition). As the liberation from the conventional logic of design representation in paper-based design has occurred, the concept of form has been transformed into the concept of formation. The designer today interacts with, controls, and moderates dynamic mechanisms of computational modeling including generative processes such as currently exist in animation and parametric techniques. How and why interaction takes place still remains a central question of performance-based systems. Can the meta-model enable a direct response to the data input of performance analysis and obviate the intervention of the designer? Where, at what point, and how should the designer intervene in the digital process still remains one of the challenging questions of performance-based design systems.

3.4 Optimization

Malkawi [22] has presented a comprehensive review of currently available environmental performance evaluation systems for architecture and engineering. He states, “to shift the conventional use of such tools from analysis to analysis and synthesis, a renewed research into utilizing advances in optimization is underway.” Relative to the potential for performance-driven design, how can performative data be exploited directly as data input in parametric meta-models? Furthermore, how can optimization techniques and multiple criteria be integrated within the process of form modification?
in parametric models in order to control the processes of modification? These appear to be root conditions for the advancement towards performance-based design.

3.5. Generation

The potential for systems supporting “performance-based generation” will require new approaches to generative models in architecture as well as integration of research areas related to environmental analysis. With respect to this goal there appear to be three possibilities which have been considered and discussed in the research literature [23]: topological systems (e.g., parametric systems); generative systems (e.g., genetic algorithms), and dynamic systems (animations) as models of design generation. In order to demonstrate our approach to performance-based design generation, we next present an experimental research case study into dynamic animated simulation as a generative technique.

4. Performative Design

4.1 Introduction

In Performative Design [23], the object is generated by simulating its performance. In our approach design is defined and characterized by applying digital simulations of external forces to drive form generation. The goal of the work is to explore how performative simulation processes can generate design. In order to demonstrate the approach we present an experimental project done in the research framework of a digital design studio [24]. This project experiments with methods for exploiting dynamic simulations to generate designs.

4.2 Experimentation with performance-based design generation

The given task was to design a building skin that might protect a building from sun penetration.

The building skin is a responsive surface that integrates two layers. The internal layer is a constructive skeleton that supports an external skin-surface layer (see figure 1). The external layer is a surface-skin composed of integrated dynamic scale units (see figure 2). The external layer is composed of scale units that behave as a system of integrated operable modules. Finally, the wall is to be design in such a way that sensors will activate the mechanism embedded in the skeleton to support and modulate the dynamic movements and the openings of the scales (see figure 3).
Figure 1. Constructive structural wall (contribution: Shoham Ben Ari and Roey Hamer)

Figure 2. External skin layer composed of dynamic scale structure (contribution: Shoham Ben Ari and Roey Hamer)
4.3 Studies and methodology

The goal of the experiment in performance-based generative design was to study and explore the following issues:

• Exploring ways to employ simulation as a generative design tool.
• Exploring animation as simulation that drives automatic form-generation.
• Exploring the necessary conditions of geometrical framework that support automatic form generation.
• Experimenting with performance-based design generation; study the visualization of formal effects and the formulation of generative processes.

4.3.1 Simulation as a generative design tool

As mentioned above, simulation tools in digital environments are currently employed for testing, evaluation and modification of prototypes in virtual design environments [25]. They also enable rapid design feedback and support design modification processes. These are still based on human-centric design approaches in which the human designer/engineer evaluates the simulation results and modifies the design accordingly.

An objective of the design experiment presented below was to study how design can be generated as an integral part of a simulation process. In the following section, we present an experimental design study after introducing concepts which are relevant to the approach.
4.3.2 Employing animation as a simulation tool

According to Lynn [26], shape can be formed in response to a dynamic environmental context. In his approach ‘the context of design’ may become an active force that drives information to transform a static form. Lynn was the first to demonstrate animation as a design tool and change its traditional role from a form-representational medium to a form-generation medium. In our case, both the context (wind) and the form (surface) are dynamic. Instead of treating design as a static form, animation was employed as a simulation of dynamic forces in order to generate dynamic form.

We have exploited animation to study the motion of a complex surface-skin. Animated techniques in 3D MAX were employed to model simulation processes and their dynamic effects (see figure 4 and figure 5). The geometrical model includes both global and local geometry. The basic geometry of the surface-skin (global geometry) was first defined as a standard surface plane primitive. A scale unit was modeled and duplicated in relation to the surface-plane. The scales were integrated as ‘local constructs’ keeping parent and child relations. The relation between the global geometry (the surface-plane) and its local components (the scales) was created according to desired number of units, the dimensions and relations of the geometrical parameters. The whole system was defined as a 3D dynamic geometrical network (see figure 4). Any dynamic movement of the plane triggered the location and related angle of the scales. At a later stage the surface-skin was defined as a cloth material by adding a ‘Reactor Cloth’ modifier to the plane.

In order to study the dynamic motion of the surface we selected wind force as a case study. Simulation of the dynamic factors and their effects on the surface were formulated by using reactors. Reactor is a plug-in for 3DS Max that allows animation to simulate complex physical scenes. The physical attributes of the surface were set up by specifying a reactor for the surface-skin. The second reactor in this experiment was a ‘Reactor-Wind’. Both supported the cloth simulation and the physical behavior of wind. The physical parameters of the surface were set up by specifying a reactor for the surface-skin, physical parameters of the surface such as: mass, density, elasticity, stiffness, stretching and damping were defined in order to simulate the dynamic environment. Wind simulation, in fact, generated the shape of the surface-skin.

The second performance factor was light. The lighting condition below the surface-skin (see figure 5) was a result of reaction to the wind causing the opening or closing of scales. At this stage they enabled visual evaluation in order to study the impact of skin geometry and scale position on light penetration. At a later stage we intend to simulate both the wind situation and the lighting as two generative factors.

Animation was employed as a form-giving mechanism. The motion of the surface and its associated scales were visually animated. The dynamic
movement resulted in generating varied surface-curvature of the skin. Any change in the curvature of the animated surface propagated to the location and the angle of the scales on the surface according to pre-defined relationships (see figure 4). In this experiment force simulation and motion were employed to generate a form. The animation produced transformation of the complex surface and the form of the surface was, in fact, the result of a dynamic force.

The aim of informed results of desired light penetration was to modify scale parameters. In a future development of an advanced system we hope to achieve modifications that will be driven automatically by the performance model. In order to achieve this, we aim to build a parametric model to support an informed form generation process.
4.4 Summary

The experimentation studies have demonstrated how performance simulation might be employed as a design tool to drive design generation. A future objective in employing this type of performance-based generation is that the formation of a skin/structure assembly may actually be generated by dynamic simulations. Furthermore, simulations and analyses of componentized assemblies may be highly relevant in the design of complex external wall assemblies, particularly dynamic assemblies.

The implications of such an approach can be broadened to include simulations of both quantitative and qualitative aspects. Such applications require the formulation of generative performance in simulation models. This might include, for example, parametric systems which can adapt the skin elements in response to the dynamic simulations.

5. Conclusions

During the last decade performance-based design, as discussed here, has emerged as a leading edge of digital design practice, research and development. With it has come a new maturity that promises to transcend the formal and geometric innovations that have strongly promulgated the great interest in emerging digital technologies. It is within the context of an emerging pragmatism that performance-based design and other approaches offer such great promise. Steps away from ‘form making’ and towards ‘form finding’ processes constitute a legitimate form of paradigm shift in architectural practice. The operative successes that we have presented may provide additional perspectives of the professional future.

Without any doubt this first generation of performance-based design has enabled the elucidation of concepts, research issues and developmental priorities. The nature of architectural meta-models that exploit these emerging technologies presents a broad field of computational research for which some decades of design research has well prepared us. Furthermore, the nature of architectural education will be strongly affected by the presence these bodies of knowledge. The realization of the vision of designer as digital tool maker is an essential prerequisite for progress in these directions.

Given that throughout this report we have attempted to map the boundaries of current practice including certain directions for experimental research, it remains now to ask what other developments might in the future become integrated with digital practices, methods and techniques. For example, future directions for development are digital techniques that couple principles of performance with principles of geometry related to form, structure and material [27]. The vision of morphogenetic design still demands research work in generative systems that are capable not only of digitally capturing the genius of nature but are potentially well-integrated.
into models of architectural design. In the coalescence of a generative approach that integrates advances in architectural and computational modeling with new approaches to modification and generation that are compatible with these models perhaps lies one possible future for design computing in architecture. Work in Performative Design is an incentive for such thinking as well as a frontier of both digital design research and professional change.

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