Form-making with special effect simulations

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Recent computational technologies expand the formal language of architecture and renew research in the nature of design creativity. While design outcomes often challenge established geometries and traditional architectural forms, they frequently converge on broader aesthetics of contemporary design, taking cues from other creative disciplines such as product design.

While digitally inspired thinking allows for a broader reading of architecture, promoting innovative and unique designs as well as new expectations regarding its spatial, formal, and material characteristics, these emerging designs often exist exclusively as visual propositions, deprived of a deeper structural, constructional, or functional logic.

Structural analysis software has helped engineers in calculating sophisticated structural models and understanding the intricacies of complex structural strategies. However, the ability to model such structures is seldom utilized in the development of architectural forms, and in everyday practice it rarely informs the design process or design criticism. Consequently, these two parallel activities (advanced structural modeling and architectural form making), while promising in their individual capabilities, have not yet been synthesized. The use of building information modeling (BIM) software has begun to integrate these processes; however, for the most part, designers and engineers continue to operate within classical, architectural-versus-structural paradigms. This still un-reconciled gap between architectural and engineering modes of production calls for further research into means and methods for the unification of the design approach.

In an attempt to integrate these parallel developments, an emerging design approach uses computational building performance simulations to create a new relationship between building technology education and architectural design studio teaching. The renewed interest in building technology in general, and performance simulations in particular, sets new expectations for digitally based architectural education and practices. It sets an expectation for architecture to behave like a 21st-century structure, not merely be fashioned to look like one. Performance-based design is a particularly promising direction in regard to architectural generative processes in which a form can be not only evaluated based on the performance criteria, but also derived through the very process of simulation.

Performance-based simulation is emerging as a critical component of the contemporary design process [1] [2], where it can function as a mechanism for the generative design validation. Performance-based simulations could facilitate human design by interactively responding to design parameters or function as semi-intelligent, self-optimizing agents that preselect promising generative scenarios and then channel them through a hierarchical portion of the design production (BIM software). The genetic algorithm (GA) [3] [4] and other evolutionary algorithms (EAs) are among the strategies that integrate structural analysis with architectural design. [5] For example, Schein and Tessmann have developed a procedure for the space truss optimization based on a collision detection analysis. However, this and similar tools are still in the developmental stages and are harder to implement in a classroom context to test complex designs.

This paper focuses on the strategies for generative design validation with the use of digital simulations, particularly dynamics-based modeling tools. Specifically, tools that employ rigid/soft body dynamics such as cloth simulations, forward and inverse kinematics (FK/IK) as well as particle interactions. This approach was used in a classroom setting as an alternative, or perhaps a complement, to other methodologies such as Genetic Algorithm (GA). My interest in this approach was dictated not only by relatively unexplored possibilities associated with this toolset, but also by its applicability as a teaching tool in an academic context.

Dynamics-based Designs

The gap between generative design tools, which are often used to pursue exclusively formal gestures, and building modeling tools (BIM) is narrowing. Generative tools start considering form's performance as well as material behaviors, while BIM tools define architecture as a parametric, spatially resolved object that can be freely manipulated and explored. This mutual convergence is particularly effective in a scale of design components, where individual elements and properties can be parametrically interrelated.

For example a rigged, IK bone system can demonstrate behavior similar to parametrically controlled composite beam-column. [fig. 1] Both are defined by degrees of freedom as well as controlled by a set of constraints. While there is still a need to develop ways to effectively bridge these two digital design environments, the strategies for forming this connection emerge with parametric simulations and dynamics playing key roles. Consequently, dynamic based simulation not only create an opportunity for design validation, but also form a natural stepping stone towards parametrically defined architectural models (details) that could be utilized throughout the entire design process.

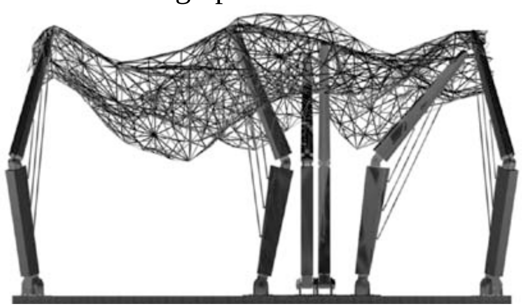

Figure 1 IK/Cloth hybrid structure after translation into BIM model with parametrically controlled columns.

Recognizing this opportunity and testing design possibilities afforded by this approach became a central theme for a class taught by the author. Students in the class focused on traversing this 'continental divide' between generative and building modeling software with promising, yet hard earned, results. Students' work discussed later in this paper shows this convergence.

Classroom Focus

Special effects tools such as dynamics, cloth or inverse kinematics (IK) can facilitate form finding in a more intuitive and visually accurate way than traditional digital modeling tools. Further, this intuitive and visually accurate way is coupled with a usually instant feedback typical to dynamic simulation. This combination of increased accuracy and interactivity brings a new promise to digital design as well as to design education.

Dynamics tools such as cloth, particles or IK bring a combination of interesting characteristics together into design. On one hand, they are very suggestive, visually inspiring modeling tools that function well as generative tools. On the other hand, they start considering material and form behavior, and as such bring a component of real live performance into design. Both of these interactions are processed interactively, unlike more involved simulation tools such as Finite Element Analysis (FEA). [fig.7]

In the class, we focused on design methodologies relating to the use dynamics-based tools. We looked at approaches that incorporated optimization and form generation mechanisms. Specifically, mechanisms that openly consider form, but also interact with simulations in a bi-directional manner. This bi-directionality becomes a vital component in the form generation feedback loop. While the form finding could have been achieved in various software packages, an ability to animate transformations and interactively change design parameters was seen as crucial feature of an effective generative tool. Animation tools allow for scanning entire spectrum of possible solutions by analyzing a class of objects rather than an individual instance.

Furthermore, animating simulations puts a particular design scenario in a wider spectrum of design performance. "Generating new forms while also having instantaneous feedback on their performance from different perspectives (space usage, structural, thermal, lighting, fabrication, etc.) would not only spark the imagination in terms of deriving new forms, but guide it towards forms that reflect rather than contradict real design constraints." [6]

The class engaged these possibilities by employing dynamics simulation tools that are used in other industries, specifically, for the creation of special effects, gaming and character animation. [fig.2] While this may seem as stepping outside a scientifically defined education, these tools were readily available and were well integrated within a small number of software packages. Since we had to rely on the set of software that students felt most comfortable with, as well as the need to cover a number of different simulations, we opted for the 3D Max/Maya approach with some data portability to other structural analysis software. This helped students to reduce the learning curve and optimize the software knowledge they currently held.
Following examples show specific applications of dynamics tools such as rigid/soft body dynamics, forward and inverse kinematics (FK/IK) and particle systems. While each of them represents a narrow aspect of design performance simulation, a combination of them quickly becomes a potent design tool.

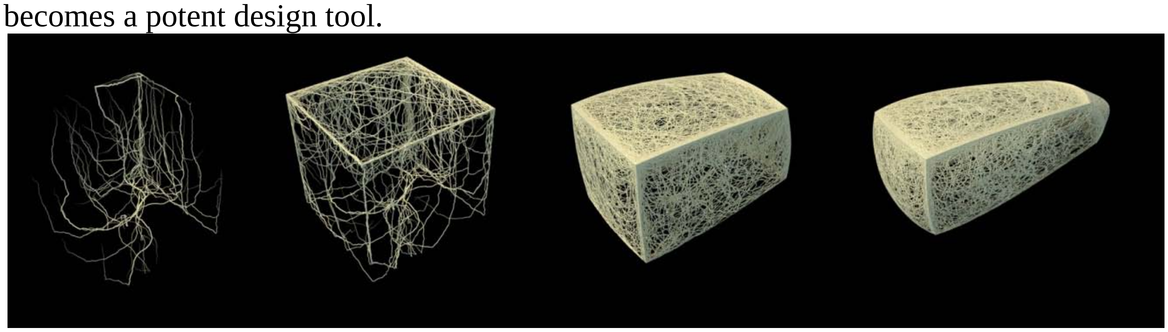

Figure 2 Generative form-finding. A semi-autonomous "vine" negotiating its growth in the relationship to continuously morphing form.

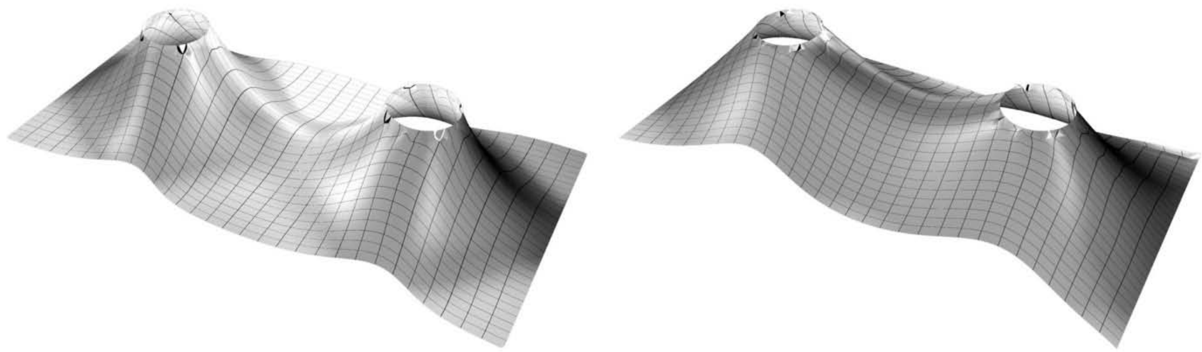

Figure 3 Cloth simulation example ; variations in material properties result in different catenary shapes

Cloth behavior exemplifies generative properties of performance-based simulations. Cloth simulations, by the very nature of this material, follow the stress flow exactly and visualize the logic of a form. For these reasons, students were asked to develop a number of cloth simulations that would mimic a fabric-based architectural structure and purse material and geometric limits. Software packages provide a wide range of material properties such as weight, flexion, stiffness or friction.[Fig.3] They also consider physical forces including wind and gravity. In result, one not only can model a spatial configuration of the cloth object as a response to acting forces, but also include material properties allowing for tearing limits and fractures. [Fig.4] This interdependence between performance of a form and material parameters brings a certain level of reality into design discussion, even when particular units or physical values are not immediately understood by students.

Cloth dynamics-based simulations are analogous to rigid and soft body dynamics in its ability to incorporate physically driven behavior. An architecturally interesting extension of these capabilities is the ability to animate a cloth behavior with the use of colliders. Colliders in this application provide a skeleton for a canvas like membrane that has the ability to react dynamically to skeleton’s reconfigurations. In such designed object, cloth becomes a dynamic skin that repositions itself based on the changed geometry of the collider framework. This can be achieved in the context of animated mesh or dynamics-based objects such as particles or bones.

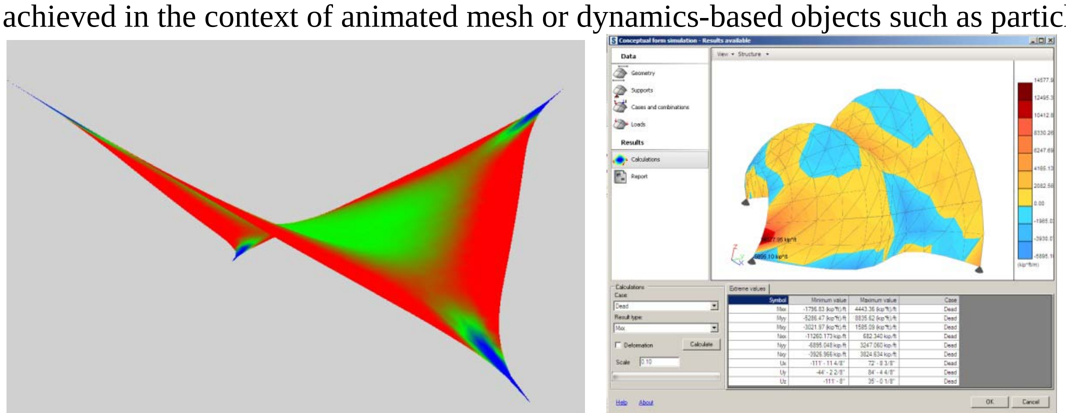

Figure 4 Cloth tension map; red color indicates fabric in tension and blue color indicates areas of compression. (left); Similar results achieved with advanced Finite Element Analysis (FEA) simulation software. (right)

Inverse Kinematics techniques, adopted from character animation modules, were used investigate structural skeleton systems with integrated and interconnected framing members that mimicked sophisticated architectural structures. [Fig.5] The ability to rig complex bone arrangements into hierarchical system with a small number of control points, allows for interactive and intuitive structural configuration. New skeletal shapes can be quickly derived from repositioning a small number of control points. After solving IK chain and hierarchical structure of the bone system, IK framework was connected with a cloth object. Resulting composite design integrated cloth with bone framework and could have been simulated dynamically as a single, morphing object.

Figure 5 IK bone system helps to control structural frameworks

While using IK in defining structural frameworks creates certain limitation in type of design solutions one is able to achieve, it also allowed students to purse unusual and imaginary designs without need to resolve constraint requirements necessary in BIM system.

Particle systems bring yet another simulation opportunity into design. In my course, students used them to evaluate aerodynamic properties of an architectural form. This was a narrowly defined approach dictated by a wide range of various simulations they were expected to do. Other possibilities for particle system applications include aerodynamic simulations of urban spaces as well as smoke and fire spread in buildings.

The most interesting characteristics of a particle system are particles physically driven parameters. Particles can be designed to interact with other objects in a dynamic way, as well as to interact among each other. These inter-particle collisions not only allow modeling a particle system as a comprehensive force, such as wind, interacting with a building, but also within itself due to its volumetric properties. [7]

Reconciling Differences

After the initial development and simulations of generative designs students were asked to transfer them into BIM environment for further analysis. The path from generative to building modeling software was difficult and convoluted. Students often had to use other software packages to make transitions possible. This could have involved rebuilding a cloth surface in Rhino or recreating structural elements that behave like IK bones in Revit. While there are not direct and easy ways to go back-and-forth between various software, the process of ‘crossing the divide’ was educational and gave students better understanding of design possibilities afforded by various software packages. Additionally, by recreating IK chains in BIM software students became exposed to the logic of constraints and degrees of freedom.

Dynamic toolsets can define design in ways that would be difficult to arrive at with more traditional digital techniques such as NURB or solid modeling. This became particularly evident to students in the class who were attempting to recreate certain aspects of their IK models within

BIM software. They quickly realized that using a constraint system of IK produced results faster than fully parameterized and initially less constrained BIM model/object.

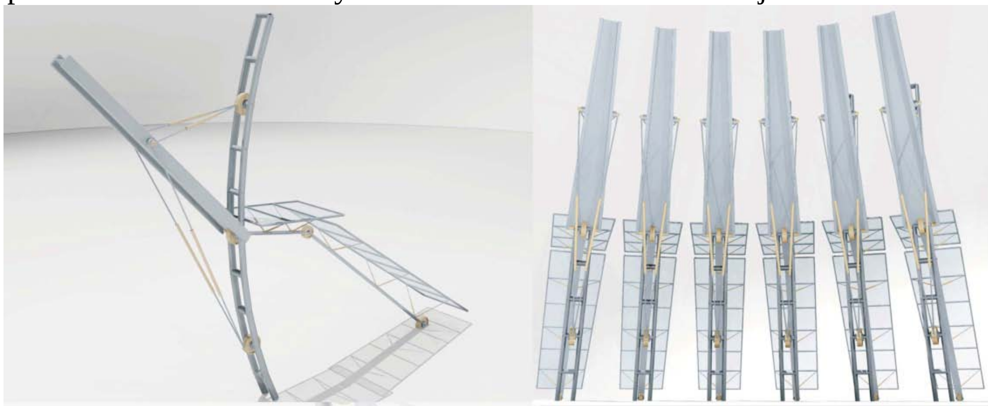

Figure 6 IK system after translation into BIM model with parametrically controlled components.

Students learned from constraint and parametric models how to define parameters in a way that brings flexibility into a design system, but at the same time, define parametric flexibility that would not over-constrained their designs. Since each new parameter introduces a set of constrains (parameter range) a large number of parameters may result in increased constrains or inability to resolve them.

This parameter versus constraint relationship allows students to realize that creativity of solutions is achieved not by excessive "parameterization" of their design objects but rather by balancing parametric freedom and simplicity of an approach—structuring parameters for effective and creative use.

Dynamics–based generative models can become stepping stones for parametrically driven BIM models. This tendency can be seen in case of CS- FEM plug-in for Maya software,[8] which is a further step towards integration of generative and validation tools within a single design environment.

This pedagogic approach builds on the notion postulated by Eduardo Torroja in 'Philosophy of Structures', where he emphasized the priority of qualitative over quantitative structural thinking. [9] Computationally-based digital structural simulations address Torroja' postulate of qualitative structural thinking. They do it in a way that emphasizes a structural model with calculations being a critical determinant, but not primary visual communication component. Consequently, computer-based simulations can become a core element of structural design education by forming 'connections with ideas'[9] and creating opportunities for students' educational development.

Additionally, digital simulations allow students to look at more complex structural systems and to better understand their behavior. Specifically, educators can extend structural teaching models into interdependent systems that consider an entire structure. While calculations, in an architectural class context, usually stop with statically determinate structures, digital simulations can easily be extended into statically indeterminate systems such as continuous beams, at the minimum. This is an important distinction between traditional and computer assisted teaching methodologies. Traditional structural education would focus calculation-based learning on individual structural components such as a beam or a column. It would address integrated systems or complex framing in a descriptive, not computational way. Students would be told how a system would behave like, but would not be able to experience it by themselves.

Coincidentally, these complex systems need to be visualized most often because their behavior is less common-sensical to students as compared to simpler models. Unlike the flexion of a beam or a column, of which a student might have had observed a similar phenomenon on his or her own in the past, complex and integrated systems typically lie beyond our immediate experience. As a result, we often calculate and experiment most with structural examples that are the easiest to experiment with, but also the least educational since they often are already intuitively understood by students. This realization is not proposing an elimination of simple model simulations, but rather argues for extending those simple models to understand them as components of a broader interdependent system.

Benefits of Digital Simulations

The development of an intuitive knowledge with the help of discussed tools may to some extent compensate for a lack of experience. This pedagogical approach responds to Michael Polanyi's "Theory of Personal Knowledge" where the author observes that knowing is an art form in which the knower understands significantly more than he or she can articulate. This comprehension of external facts without being aware of them specifically, called 'tacit knowledge', accounts for human ability to function in the world. "…tacit knowledge forms an indispensible part of all knowledge,' [10] and this is this part of knowledge, which allows us to process meaning and reach goals beyond our verbalized or processed thinking. Confidentially, what we often call experience is closely related to, such defined, tacit knowledge. This connection suggests that experience can be reinforced or partially substituted by other forms of learning. Simulations can be one of those.

Additionally, an ability to ground a student in a physically based knowledge of architecture. In this sense, digitally based simulations relate to the teaching of materials and methods or building technology, since they bring physical properties and dimensionality to abstract designs.

Final Thoughts

In recent years, we have witnessed a growing number of papers on the topics of generative and performance-based designs. These studies focused on theoretical underpinnings and/or relatively narrow applications that addressed particular functionalities. This study attempts to broaden this framework into multiple dynamics tools by interconnecting them into an integrated and comprehensive model. This is seen in an example that combines multiple dynamics tools, such as inverse kinematics (IK) and the cloth engine interoperability, into an architecturally relevant model.

Furthermore, this case study (student work) interrelates behavioral aspects of the dynamics-based tools with database models. It specifically maps individual capabilities and correspondences between both platforms and proposes a direction for further developments in the BIM platform. It shows the need for and opportunities associated with combining behavior-based and database characteristics into a single design model: broadening BIM not only as a database, but also as a behavior/performance model.

Finally, this case study allowed students to discuss an integrated design process, first by developing strategies for conceptual design and later by recreating conceptual designs within the BIM platform by mapping relationship between dynamics and BIM tools.

This simulation-based, interactive approach shifts the students' focus from the visualization of buildings or data to the visualization of physical processes and behaviors. The move is from static to more dynamic thinking. Consequently, through the use of dynamics-based software, a new and promising direction in generative architectural design emerges. An architectural form not only can be analyzed based on its structural performance, it can actually be *derived from the process* of generating structural simulations. This method of form generation brings the promise of greater design integrity within new creative horizons.

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