Considering Physicality in Digital Models

Andrzej Zarzycki
New Jersey Institute of Technology, USA
andrzej.zarzycki@njit.edu

Abstract. *This paper discusses the integration of physical and digital models in the context of building technology teaching. It showcases projects that explore the design possibilities of a chosen structural system with the use of parametric and behaviour-based computational modelling. It uses detailed mock-ups as vehicles to study, optimize, and evaluate the design as well as to provide feedback for student learning and the direction in which future designers may engage computational design. Finally, it investigates digital-to-physical design translations, the importance of which becomes more and more critical in the context of the current, computer-intensive architectural education and professional practice.*
Keywords. *BIM; building information modelling; parametric construction details; construction assemblies.*

INTRODUCTION

With digital tools firmly established in professional practice and academia, the question of the continued relevance of physical and traditional methods is often overlooked or unexamined. Certainly, there are passionate statements being formulated on both sides, with analog thinking more and more on the defensive. However there is a need for closer investigation of the analog-to-digital and digital-to-analog phase changes to further improve the development of computational tools and digitally driven creative processes.

This paper looks at the close integration of physical and digital models in design practice and investigates the ways both design environments inform each other. The goal of this paper, however, is not to justify why we need physical and traditional modes of thinking, but rather to point to needs in the further development of computational design thinking, which in many aspects is still not up to par with the traditional (not digital) design process. The intuitive, even haptic, use of tools; a natural conceptualization framework; and the lack of physical considerations are just some of the issues waiting to be addressed by the computational creative framework.

This paper specifically looks at materiality embedded in architectural models, their physically based behaviour, and the haptic feedback designer and makers receive when interacting with their products. The emerging question is what forms of digital software and interface would provide a comparative level of interactivity: what software features and design interface would facilitate full virtualization of the design process.

PHYSICAL-TO-DIGITAL TRANSLATIONS

To research the topic, students investigated structural systems that actively informed architectural tectonics (form-active structures) and explored their design possibilities with the use of parametric and/or behaviour-based computational modelling. Once the research phase was completed, students deve-

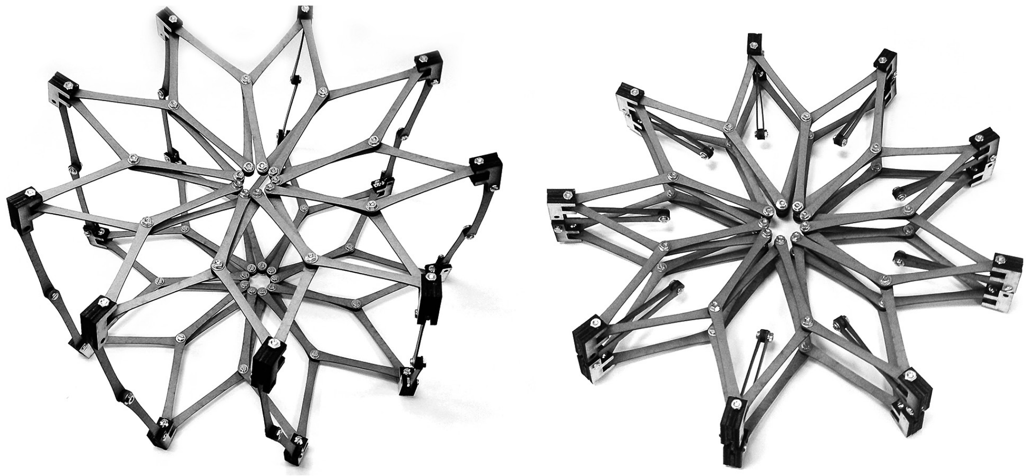


Figure 1
Deployable structural framework, conceptual model.

loped a number of physical mock-ups of the final designs to compare their behaviour with computer simulations they developed earlier for the same design.

This allowed students to reflect on the materiality of digitally designed architecture, to understand the opportunities and limitations various design tools provide, and to visualize structural behaviour in more intuitive and direct ways that available with digital tools alone. The following examples illustrate the process and discoveries students made.

Adaptive Forms

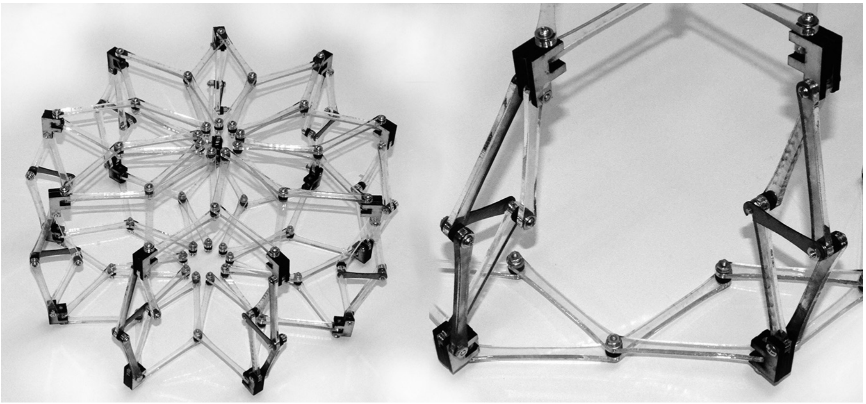
A number of projects looked at scissor-like mechanisms to develop shading and spatially adaptable systems. The project in Figure 1 investigated a deployable assembly that can be a temporary structure or an adaptive space.

Initially, students researched various relevant precedents that dealt with temporary, portable, and deployable structures. This research gave students insight into different kinetic systems, assemblies, and material applications. Students were particularly interested in the ability for the design form to be contracted into a relatively small volume and to have a low total weight. Immediately, these prerequisites started to point to the solutions of using light metal framing with a possible fabric enclosure.

In the second stage, students developed a number of conceptual studies that allowed them to apply researched systems into new spatial configurations and test their appropriateness. After developing a number of designs, both physically and digitally, students focused on the solution that followed the logic of the Hoberman Sphere. Similarly to Huberman's design, the student structure was capable of folding down to a fraction of its fully deployed size. It also used a version of a scissor mechanism. Instead of a sphere-like configuration, students experimented with a cylindrical form with the ability to expand both vertically and horizontally by increasing the cylinder radius.

After completing the chipboard model and interacting with it, students realized that the proposed structure did not have the desired rigidity and durability. Components had difficulty supporting themselves, resulting in sizable deflections. When expanding and contracting the structure, individual components were subject to twisting in the joints, resulting in kinetic friction and deformations. While this is rather obvious observation with a model made of chipboard, students also noticed

Figure 2
Deployable structural framework, conceptual model.



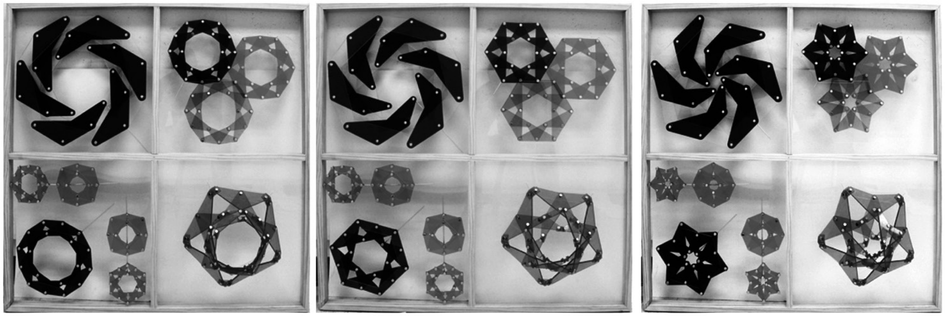
possible issues with the actuation of the kinetic assembly. While displacing only some, not all joints, at the same time, the softness of structural components was causing the entire system to deform, putting additional stress on connections and causing material fatigue. This was important feedback for students, since it suggested that the scaled-up structure, even when made with higher-grade material, may still have similar rigidity and stability issues.

The subsequent study model introduced more rigid material (acrylic glass), sized up the cross-section of individual components, and doubled vertical structural members. The locking mechanism was added to further stabilize the structure by introducing triangulation in the vertical supports (Figure 2).

The second project started as purely two-dimensional shading system and evolved to incorporate three-dimensional composition (Figure 3). Students similarly started by analysing various expandable designs that used scissor-like mechanisms. Their focus was on using scissors both as a structural element and as an adaptable enclosure/shading. By testing various scissor joint geometries, they looked at possible shapes and the resulting planar tiling to provide a variety of expressions of a façade shading system.

The physical and digital explorations revealed a number of intricacies, both technical and geometrical, that were not immediately evident at the beginning of the project. What seemed like a straightforward design quickly became a complex project, particularly when multiple instances of a scissor mechanism were interconnected into larger assemblies (Figure 4). The attachment details became

Figure 3
Façade screen mock-ups.



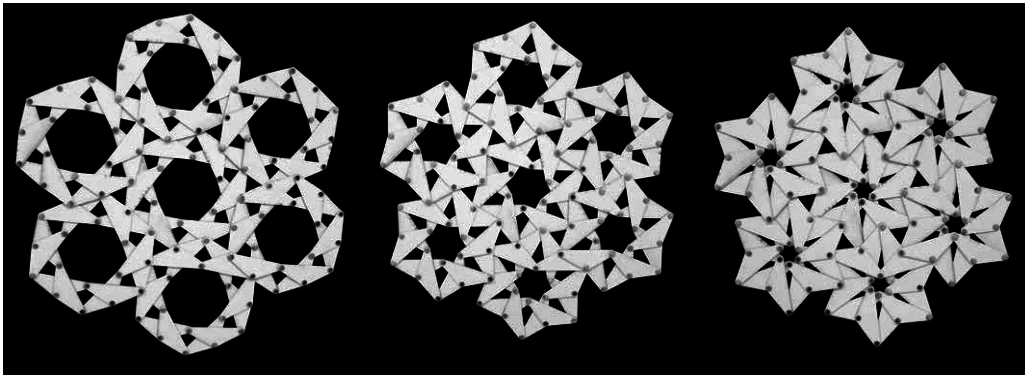


Figure 4
Aggregation of individual assembly components.

more involved, with diverse rotating and sliding motions occurring within the component connection. The connection had to account for competing movements between various sub-elements. One of the studies employed a three-dimensional version of the scissors mechanism to form a dome-like structure (Figure 5). To accommodate the three-dimensional rotation of scissor plates, students developed wedge-like adapters to control the curvature of the resultant form. Unlike other groups working on kinetic designs, this team relied heavily on physical models to complement their digital simulations. Students felt that the tactile qualities of physical models gave them valuable feedback about the levels of friction within joints and material resistance. Particularly in the situations when digital models were getting easily over-constrained and locking themselves in a fixed position, physical prototypes, due to their relative imprecision and material flexibility, gave a better indication of the overall assembly behaviour. They were also more informative because they provided a tactile feedback that helped to advance design. While laser-cut mock-ups allowed for a high level of precision, the initial prototypes were developed in the more forgiving medium of chipboard, as compared to later prototypes made of acrylic glass. This helped to track kinetic movements, particularly registering material fatigue and failures for further design refinements.

While physical and tactile feedback was important to the team, there were also limitations involved in deferring exclusively to physical mock-ups. It was often difficult to distinguish between minuscule kinetic transformation and fabrication toleranc-

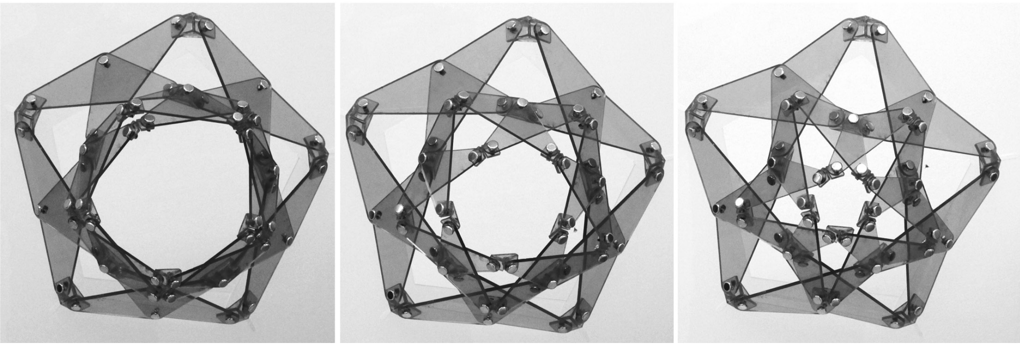
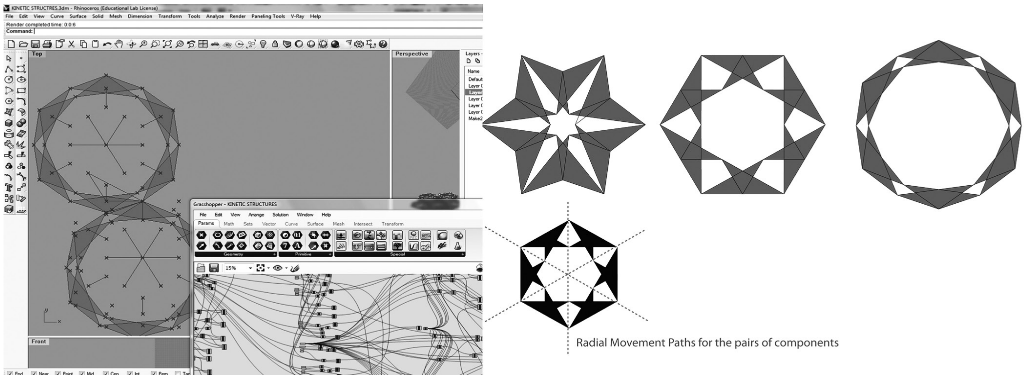


Figure 5
Applying scissors mechanism to a dome-like structure.

Figure 6
Testing parametrically geometric relationships between various components.



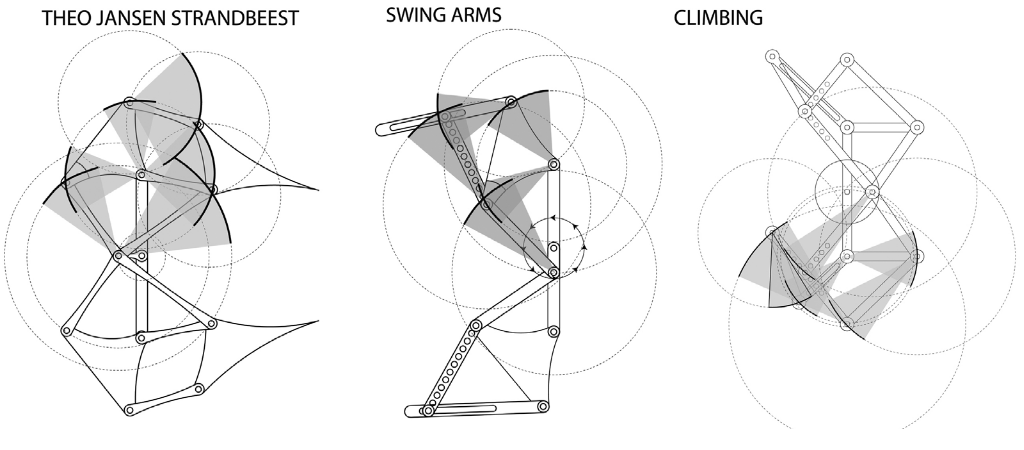
es as well as material's ability to hide stress through deformations (strain). Whereas material deformations may seem a desirable quality, these deformations may ultimately lead to material fatigue and assembly failure. To address these concerns, the design team used parametric digital models to validate their findings and fine-tune the final set of physical mock-ups. These parametric models allowed for effective tracking of numeric values and maintaining geometrical relationships between various components (Figure 6).

Once students established a general understanding of kinetic system behaviours, they became significantly more efficient in developing variations to parametric models. They were able to implement complex assemblies in more informed and intuitive ways.

Kinetic Movements

Inspired by Theo Jansen's kinetic sculptures, students investigated parametrically defined adaptive structures that mimics skeletal systems. They started with the exact replica, both physical and digital, of Jansen's Strandbeest kinetic mechanism. Then, with parametric models, students investigated how specific component dimensions and radii impact the kinetic behaviour of the entire system (Figure 7). Parametric definitions allowed for fluid changes to a

Figure 7
A study of the kinetic behaviour of the entire assembly. Original Jansen's design (left), and student design explorations (centre and right).



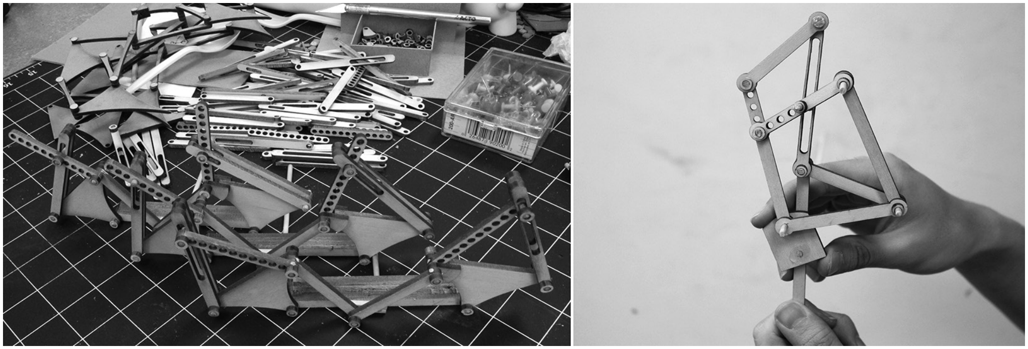


Figure 8
A kit with multiple parts worked effectively as an analog parametric study.

digital model and for immediate feedback on its kinetic behaviour. This helped to understand the role individual elements played within the entire assembly and the types of motions these elements were capable to produce.

While these parametric studies became effective tools in understanding how Jansen's kinetic sculptures worked, it became difficult to extrapolate these findings into new meaningful movements. To overcome this issue, students started with changing element proportions, folding ratios, and adding additional components (Figure 8). These speculative explorations led students to propose and develop an adaptable vertically climbing mechanism that used core principles of Jansen's models with changes to the types of constraints and possible motions.

Kinetic designs such as Jansen's sculptures that mimic walking structures, or Hoberman's expanding dome, require close and detailed understanding of kinetic mechanisms developed over time with multiple prototype reiterations. To shortcut the discovery process, students started with an already resolved design and investigated ways the logic for this particular mechanism can be extended to other forms of movement. While a physical working prototype was an ultimate goal for the project (Figure 9), it was easier to experiment with variations of the base mechanism using digital modelling.

However, conventional three-dimensional modelling software was not effective for this type of prototyping. The design team turned to parametric software, such as Revit (parametric BIM) and Grasshopper (graphical algorithm editor for Rhino), that was capable of dealing with constraints and passing these constraints between various assembly components. In addition to these two software approaches—parametric and prescriptive—the team briefly looked into VFX packages such as 3DMax and

Figure 9
Kinetic movements, final assembly.

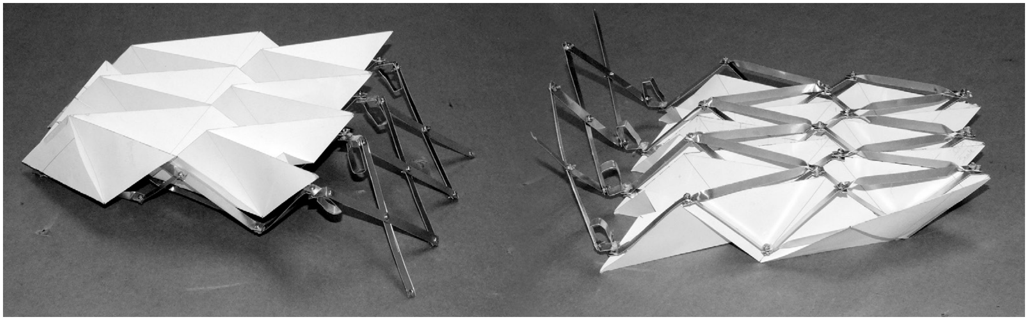


Figure 10
Rigid origami as an adaptive envelope.

Maya with inverse kinematics (IK) capabilities. While IK provided ready-made functionalities that could be applied to walking structures, the inability to directly "hack" into the algorithms behind IK functions became a significant deterrent in using them as exploration tools. Dealing with actual parameters—angle values and component dimensions—allowed students to get more direct confirmation of their initial design propositions and develop a stronger intuitive feel for the entire mechanism.

CONTINUOUS ENCLOSURES

With adaptive designs, the issue of the continuous weather tight exterior enclosure resistant to material fatigue is a major challenge. When elements move or stretch, they wear off connection seals and may cause material failures. To address these issues, students looked at form-active designs, particularly those that deploy tensile (fabric), pneumatic and foldable strategies in conjunction with kinetic assemblies.

One of the approaches looked into rigid origami as continuous yet spatially reconfigurable forms that do not rely on material deformations (Figure 10). While hinged joints provide opportunities for material fatigue, the rigid plates are durable, with all the performance qualities of traditional wall systems, including thermal and structural. Since rigid origami solutions carry a particular design signature, the underlying structural framework would naturally follow the same geometry, both from performance and aesthetic considerations. To some extent this can be seen as the limitation of the system, not only from the visual but also from the occupancy viewpoint, since the origami-generated forms are hard to reconcile with horizontal surfaces such as floors, both because of these forms' flatness and their changing height. However, they can still be effectively employed in other enclosure surfaces.

LEARNING FROM PHYSICALITY

In discussed cases, students worked with additional constraints defined by a number of component and connection types to simplify manufacturing and assembly. These became important design boundaries, focusing students on pursuing optimal solutions and driving questions of component assembly and functionality. While in some cases students did not produce an actual one-to-one mock-up, the scaled-down models became effective in setting the stage for understanding the overall kinetic system behaviour and speculating on further development of design by giving students direct feedback. The haptic feedback included not only the component movements but, more importantly, the levels of material resistance to deformations, joint frictions, and material fatigue. Additionally, physical mock-ups became a lesson in understanding issues of manufacturing precision and design and construction tolerances. These mock-ups allowed students to feel the behaviour of the material and the entire assembly in addition to visually understanding its movements.

Furthermore, the discrete numericals used in defining computational models do not help to understand the need for and the role of design tolerances. This is particularly evident in the kinetic and adaptive structures, where the movements of individual components can compound the amount of displacement and rely on material elastic deformations. The ideal computational models, BIM or not, should be able to consider these factors, and use them as design constraints and validators. Preferably, these models would provide easily understood, intuitive, and perhaps even tactile feedback that could not only evaluate but also stimulate design.

With today's generation of designers, who routinely have a better grasp of digital than of physical tools, the requirement to manually construct designs is probably even more important than in the past. Since the architectural profession ultimately deals with physically constructed buildings, there is a need for designers to understand the translation process of their ideas from the digital to the physical.

There seems to be a perception among many students that once a design is modelled in a three-dimensional virtual environment, it is fully resolved. While this may be true from the geometrical point of view, as compared to traditional two-dimensional representation of buildings where different drawings did not have to be reconciled spatially, it is not true in other aspects of design.

The present computational tools solve some of these issues but still leave many of them unresolved. Specifically, material properties, physical behaviour, and contractibility continue to remain unaccounted for in most software packages. While the approach discussed above points to ways of addressing the issues of material properties and physical behaviour, physical mock-ups prove to be an effective learning environment. By constructing kinetic and adaptive designs, students experience the intricacies of mechanical assemblies and material limitations.

The geometric precision taken for granted with software packages becomes a major issue when manually constructing kinetic designs. Centre of gravity and points of rotation are important factors in the effective operation of kinetic assemblies. The process of building and rebuilding mock-ups, discovering imprecision in produced work, facilitates the discussion on types of loads (concentric versus eccentric) and moments associated with them. Students experience first-hand the need for design tolerances and the ways they can be incorporated in their designs. Overall, students moved away from idealized computer-based reasoning toward more holistic thinking about a building as a probabilistic structure—a result of compounding imperfections and tolerances. Also, the use of advanced digital modelling tools such as BIM helped shift the design focus from the model itself toward broader and interdependent modelling of an assembly or a building (Smith and Tardiff, 2009).

SOFTWARE LIMITATIONS

Many of the physical-to-digital and digital-to-physical translations discussed above were partial and punctuated. This is particularly evident with foldable structures that utilize rigid origami. Origami designs are not easily to conceptualize and extrapolate. While there are plenty of examples of various origami designs, they tend to be difficult to extract and modify as sources for new designs (Stavric and Wiltsche, 2013). Their design requires a significant level of involvement and experience. Also, there is a limited number of software applications that can be used to explore origami design, particularly in interactive and kinetic ways. Furthermore, many of the software packages are stand-alone applications that do not port models into other applications.

For those projects, the physical modelling approach was more effective than its digital counterpart. However, the physical models did not stimulate tectonic explorations and versioning in the same ways as other projects that were realized with computational tools.

While many of the examples discussed here show only structural elements of the larger assembly, the question of how kinetic structures can be combined with an adaptive façade or building skin system is critical. For this reason, a number of students looked into form-active systems such as tensile, pneumatic, and foldable structures to see how they can be combined with kinetic assemblies to provide both adaptability and continuity of the enclosure. Consequently, a number of student groups adopted a form-active approach towards a façade or a building envelope to work with kinetic structural systems, while other students focused exclusively on the form-active design for both structure and building envelope.

DISCUSSION

Adoption of digital tools in design serves as an opportunity to redefine existing teaching and practice paradigms. This position is held by a number of practitioners, researchers, and educators who advocate the necessity of the design process change as a consequence of new computational tools, particularly BIM software (Mayne et al., 2006; Clayton et al., 2010). Individual authors propose various design frameworks. Some of the approaches focus on component-based design thinking, where an overall building is depicted as a combination of construction details (Wallick, and Zaretsky, 2009). Others advocate the role of BIM software in capitalizing on a tacit knowledge associated with any creating-making work (Clayton et al., 2010). This study aligns itself with the latter approach by emphasizing digital-to-physical translations and using materiality as a feedback mechanism to inform digital tools.

While tacit knowledge is generally acknowledged as critical aspect of the design process (AIA,1969), it is also evident that the formation of tacit knowledge (Polanyi, 1983) is associated with experiential learning and learning-by-doing. While the process of learning-by-doing can be informed by both digital and physical making, there is a particular benefit from bridging both modes of creativity. Since the end goal of the design process in architecture is a building or a structure, the ability to understand the connection between the digital design process and its physical actualization is crucial.

With the emerging robotic applications in architecture, the ability of BIM software to increasingly reflect the reality of the physical world and actual construction assemblies becomes critical. Material intelligence (MI) that is largely missing from computer applications, including BIM, sets unnecessary limits to the digital design processes. A file-to-fabrication approach works effectively when the file creator has an explicit, or at least a tacit, understanding of the materiality of the final design medium (Perez, 2010). In addition to materiality, the physics-based behaviour functionalities would allow for greater relevance and integration of digital tools in the making of architecture (Zarzycki, 2009; 2011). The methodology discussed in this paper provides opportunities for addressing material knowledge learning and the increased convergence between digital tools and building construction.

The digital-physical design dialogue is intricate and bidirectional, involving simulations, performance analyses, and component optimization. By connecting digital prototyping with physical mock-ups, material becomes an important variable—another consideration in the otherwise parametrically driven design process. Material acts as yet another feedback loop that informs design and provides a set of constraints to guide designers (Cabrinha, 2008).

Future work will focus on material translations (Decker, 2012) from physical to digital environments and closer interaction between digital and physical modes of thinking. Specifically, I am interested in simulations of material properties and physics-based behaviour to develop seamless digital-to-physical translations.

FINAL CONSIDERATIONS

The examples discussed in this paper provide a starting point for outlining the software functionalities that are missing from digital tools and digitally enabled design processes. The ultimate aspiration is that BIM, or computational models in general, assume the role of the virtualized final constructionally real designs, with the only difference between digital BIM models (mock-ups) and physical models being that computational models are actualized before a physical structure are built. While this goal is ambitious, it is also necessary in order to bring digital design process to the level where it can be deployed universally and holistically, independent of the designers' location and individual capabilities.

The present limitations lie both in computational software that does not address a number of critical design considerations, such as materiality and physically based behaviour, and also in the interface designers use to interact with virtual models. Perhaps the latter is more challenging, since it would require incorporating more sensory and intuitive inputs and breaking away from two-dimensional displays. Ultimately this would require shifting the computational interface from a mostly visual to amore dimensional feedback system that would address multiple-sense inputs.

Purely geometrically driven digital models miss many design opportunities. What may seem a failure of resolving constraints within parametric BIM systems with physical models can be a close enough (good enough) solution that material elasticity and tolerance allow to function, giving a designer an important clue of being in the proximity of a solution. The binary quality of computational feedback may often be misleading, particularly in the boundary conditions when investigated designs lie immediately outside the zone of computationally correct solutions. A more forgiving and probabilistic approach associated with physical models and materials may often be more informative and effective as a design tool. Feeling material behaviour provides a broader design feedback than simple "works" or "does not work" (over-constrained) statements.

REFERENCES

AIA. 1969, *Architect's handbook of professional practice*, chapter 11: project procedures. The American Institute of Architects, Washington.

Cabrinha, M. 2008, Gridshell Tectonics: Material Values Digital Parameters, Silicon + Skin: Biological Processes and Computation, in *Proceedings of the 28th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, Minneapolis 16-19 October 2008, pp. 118-125.

Clayton, MJ, Ozener O, Haliburton J and Farias, F 2010, 'Towards Studio 21: Experiments in Design Education Using BIM', in Goosens., K and Agudelo, L (eds), *SIGraDi 2010 Proceedings of the 14th Congress of the Iberoamerican Society of Digital Graphics*, SIGraDi, Bogota, Columbia, pp. 43-46.

Decker, M 2012, 'Material Dynamics: Emergent Materials in Architecture', Lecture presented at the Inaugural Symposium at NJIT, Newark, New Jersey. http://youtube.com/watch?v=h3ffl2kBNKA (accessed, May 21st, 2013)

Kloft, H 2005, 'Non-standard Structural Design for Non-standard architecture', in Branko Kolarevic and Alim M. Malkawi (eds), *Performative Architecture: beyond instrumentality*, Spon Press, New York and London.

Mayne, T 2006, 'Change or Perish', in Broshar, M, Strong, N and Friedman, DS, *American Institute of Architects: Report on Integrated Practice*, AIA, Washington DC, Section 1, pp. 3-5.

Perez, S 2010, 'M.I. Material Intelligence', *Proceedings of the Creating-Making Forum*, University of Oklahoma, Norman, Oklahoma.

Polanyi, M 1983, *The Tacit Dimension*, Peter Smith, Gloucester, MA, p. 20

Smith, D. and Tardiff, M. 2009, *Building information modeling: A strategic implementation guide for architects, engineers, constructors and real estate asset managers*. John Wiley & Sons, Hoboken.

Stavric, M and Wiltsche A 2013, 'Investigations on Quadrilateral Patterns for Rigid Folding Structures', *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, pp. 893–902.

Wallick, K and Zaretsky, M 2009, 'Fragmentation and Interrogation as an Approach to Integration', *ACSA Proceedings, Value of Design*.

Zarzycki, A 2009, 'Dynamics-based tools: an unusual path to design integration', *ACM SIGGRAPH 2009 Asia Proceedings*, Yokohama, Japan, (DVD ROM).

Zarzycki, A 2011, 'Form-making Without Form Making', Proceedings of the *Parametricism (SPC)* ACADIA Regional 2011 Conference, Lincoln, NE.