LEARNING WITH DIGITAL AND PHYSICAL MOCK-UPS USING BIM

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Abstract. Computer-based tools have changed the focus and modes of design thinking in architecture. While often criticized for its overemphasis on formal expressions and its pursuit of the spectacular, digital creativity has begun to take into account a multiplicity of design factors that define architecture. These factors relate to performance simulation and analysis, constructability, and building information modelling (BIM). This paper discusses the use of physical and digital mock-ups in the context of building technology courses. It uses these mock-ups as an important vehicle that provides students with a feedback mechanism regarding often digitally idealized creative thinking.

Keywords. BIM; building information modelling; parametric construction details; construction assemblies.

1. Introduction

Creating-making is a formative constant in the ways design thinking translates into the built environment. Creating-making transcends the division between technology and handmade products or, more recently, between analogue and digital modes of production. As during the Renaissance, when ideas expressed in drawings and sketches were tested with physical models\(^1\) – mock-ups – similarly today we continuously shift between physical and digital modes of thinking and production. A significant difference today, however, lies in a tightly integrated dialogue between the physical and the digital. The digital is no longer a mere representation of the future physical (a proposed design), nor is the physical a mere realization of the digital creativity, fabricated from scale-less and context-less digital models. The digital-physical design dialogue is more intricate and bidirectional, involving simulations, performance analyses, and component optimization.

This paper discusses the integration of physical and digital models in the context of the structure course in an accredited (professional) architectural program.

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\(^1\) The term "mock-up" refers to a physical model that serves as a representation of a finished product in the design process.
It presents the student work that explores the design possibilities of a chosen structural system with the use of parametric and behaviour-based computational modelling. It uses the mock-up as a vehicle to study, optimize, and evaluate the design as well as to provide feedback for student learning. 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 education of architects.

2. Class Methodology

The class approach employed a long tradition of using physical models to evaluate design ideas. However, this long tradition has a new variable – computation – that opens unique design opportunities and resolves some limitations associated with the use of physical models as design evaluators in the past.

For the term project, students were asked to investigate a structural system that actively informed architectural tectonics (form-active structures) and to explore its design possibilities with the use of parametric and/or behaviour-based computational modelling. Later, students were asked to build a physical mock-up of the final design and compare it with computer simulations they developed earlier for the same design. Students were asked to follow these steps in the development of a term project:

- Choose a structural system that actively informs architectural tectonics through kinetic behaviours, or material simulations.
- Research relevant precedents and pay special attention to assembly details and kinetic mechanisms that can be used as departing points for design explorations.
- Develop digital models (mock-ups) using parametric geometries and/or physically based simulations.
- Test alternative designs through digital simulations.
- Build a large-scale physical mock-up and verify design assumptions from digital simulations.

The purpose of the assignment was twofold: to bring to students’ attention the materiality aspects of digitally designed architecture, with an understanding of the opportunities and limitations various design tools give us, and to visualize structural behaviour in more intuitive and direct ways.

3. Scissors and Hinges

An example of kinetic assembly is a façade screen system (Figure 1) that builds on the precedent of Chuck Hoberman’s work and the façade screens of the Institute du Monde Arabe in Paris. Students developed a number of physical and computational models to test design variations and ultimately proposed a number of two- and three-dimensional alternatives to the conventional scissor-like hinge assembly. The
physical and digital explorations were full of surprises and discoveries. What seemed like a straightforward design quickly became a complex project, particularly when multiple instances of a scissor mechanism were interconnected into larger assemblies. The connection details also became more intricate, with diverse rotation and sliding motions occurring within the assembly. Some of the design explorations led students into three-dimensional versions of the base mechanism that resulted in dome-like assemblies. Students had to develop additional wedge-like adapters to control the curvature of the resultant form and to accommodate the three-dimensional rotation of scissors plates. Unlike other groups, this group of students 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 became over-constrained and locked themselves in a particular position, physical models, due to their imprecision, gave a better indication of the overall assembly behaviour.

4. Rethinking Theo Jansen’s Models

Inspired by Theo Jansen’s kinetic sculptures, students investigated the design possibilities of a parametrically defined adaptive structure that mimics skeletal systems found in nature. They started by creating an exact replica, both physical and digital, of Jansen’s Strandbeest kinetic mechanism. Then, with parametric models, they looked at how specific component dimensions and radii impact the
kinetic behaviour of the entire system. Parametric definitions allowed for fluid
cchanges to a digital model and for immediate feedback on its kinetic behaviour.
This helped students to understand the role individual elements played within the
entire assembly and the types of motions these elements were capable to produce.
These 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 prototypes. Similar developments
would not be easily achieved within a semester-long three-credit course. To short-
cut the discovery process, students started with an already established design, in
this case Jansen’s walking mechanism, and investigated ways the logic for this
particular mechanism can be extended to other forms of movement. While a phys-
cical prototype was an ultimate goal for the project, it was easier to experiment with
variations of the base mechanism using digital modelling. However, conventional
three-dimensional modelling software would not be an effective environment for
prototyping. What was required for this particular project was parametric software
that would deal with constraints and be able to pass them between various com-
ponents. Revit (parametric BIM) and Grasshopper (graphical algorithm editor for
Rhino) were suitable software environments for this project.

5. Kinetic Wings

Inspired by Santiago Calatrava’s sunshade mechanism, the project (Figure 2) looks
into providing a kinetic canopy with expressive wave movement. Students devel-
oped a number of prototypes, originally using Rhino software, and later physically
building scaled-down models while testing various materials. Student testimonies
below explain the development process along with the technical issues they faced:
“While putting this model together, we realized that the acrylic pieces were not
strong enough to resist the turning motion that was being applied to them. Parts
began to fall apart. To solve this problem we had to remove one wing to lighten the
weight and cut the larger openings in other wings without reducing rigidity.”

Learning from the first model, students developed a second prototype “that...is
smaller in scale and is composed of different materials. The reason we did it was
that the first model was made of acrylic which was more fragile compared to the
originally intended wood. The bending effect happening to the acrylic was pre-
venting it from moving the way that it should.”

What students also discovered, and what is not evident from the above testi-
mony, is that material substitutions may not always work unless the overall design
or the design of individual components is appropriately adjusted. For example, a substitution from wood to acrylic may require changing the thickness of elements or redesigning their profiles to increase rigidity. Similarly, the impact on the friction associated with the component rotation should be considered.

6. Umbrellas

Another kinetic project used an umbrella mechanism as a departure point for adaptive structure. Starting by recreating an umbrella mechanism using the Revit software, students linked individual assembly components with explicitly geometric relationships (trigonometric functions/expressions). Students focused on developing design alternatives to the basic mechanism that investigated different forms of hinging of components and folding of the overall design. Part of the design and production focus went into mechanical controls of the mock-up with an Arduino microcontroller and sensors, in a similar way as the canopy project mentioned earlier did. In this case, the aperture of the umbrella was correlated with the light sensors positioned immediately below it.

Both projects, the canopy and the umbrella, used a simple mechanical precedent as the initial idea for the kinetic assemblies. While the final designs did not substantially redefine the initial prototypes, they were valuable learning experiences. They taught students the intricacies of kinetic architectural assemblies that predominantly rely on simple ball joints or hinge-like mechanisms. They also allowed students to re-examine the purpose of kinetic structures and tie them in with a broader conceptual framework of adaptive designs and intelligent buildings. Furthermore, by laying out the framework for microcontroller operability – if-else conditional statements – they were able to define a series of functional responses to a single parameter input.

7. Pneumatic Doughnuts

While a mock-up as a partial full-size prototype can be easily achieved with kinetic structures by building a portion of the overall design, with pneumatic
(air-supported) designs a partial mock-up may not be as effective. One needs a critical mass of the “building” to have both structural integrity and air tightness. This limitation resulted in pneumatic mock-ups encompassing almost the entire design scope. The “doughnut” in Figure 3 (A and D) is an example of a pneumatic structure developed by students that went from a partial analysis and a mock-up into a full-blown prototype. Students envisioned it as a free-standing pavilion able to accommodate human activities in an unrestricted and comfortable way. The motivation behind the centrally organized form of a doughnut was to create a space that could be explored and also would allow for congregation. It appeared during the initial small-scale model experimentations that the overly linear space would provide the difficulty of uniformly inflating it, particularly if one were to rely on a single point, or not more than two points, of air supply.

Students started their project by developing initial three-dimensional geometry in Rhino software and fine-tuning its form, considering what a pneumatic structure would most likely look like. Then they used the Kangaroo plug-in for Rhino and Grasshopper to simulate the physical behaviour of initial designs. During simulations, geometries with individual mesh cells were adaptively refined until an optimized form was achieved. Since the original Rhino mesh was an inert geometry (poly mesh) without any parametric controls, the resulting Kangaroo simulation was not as effective from a design point of view as compared to a parametrically controlled mesh that could be interactively changed during simulation. For this reason, students moved from the Rhino inert mesh approach to Grasshopper’s parametric surface modelling environment and were able to explore a wide range...
of design alternatives. In addition to interactive manipulation of the three-dimen-
sional model, students were also able to control the levels of pressure and spring
values to analyse the amount of inflation and impact on design.

While physical mock-ups are an ultimate proof of concept, they narrow a range of
observations into a particular case study, tying them to a singular physical instance.
On the other hand, parametric geometry simulations gave students an insight into a
broader range of forms and their behaviours. It was often mesmerizing to watch how
a particular design evolves over time, sometimes locking itself in a particular position
or falling into itself (by folding) and effectively over-constraining itself, showing
bifurcating scenarios for the form optimization. Adding more air pressure or chang-
ing spring net properties in most cases would not reverse tectonic outcomes.

As part of the mock-up explorations, students investigated several cut-and-
unroll scenarios to find the most effective (tileable) sections (Figure 3B) to
optimize material usage and minimize waste. The material economy became an
important feature for the optimized final design. Available software did not allow
for the direct material optimization that would help to find the zero-waste solution.
For this reason, students had to study it in a recursive, indirect way by developing
alternative unrolled sections and comparing them side-by-side to derive the most
efficient approach. (Figure 3C)

8. Discussion

While tensile and pneumatic mock-ups were full-size deployment of partial struc-
tures, the kinetic assemblies in most cases were scaled-down versions of original
designs. The reason for this approach was to reduce material and power require-
ments for the kinetic components. In the case of mechanically powered
assemblies, this allowed for the use of servos and small low-voltage motors
instead of full-size high-voltage electrical motors. It also allowed for the simpli-
fied production of the mock-ups, since most of the components were produced
with laser cutters. Even though the kinetic designs done by students were reduced-
size models, they were effective tools to evaluate kinetic structures. However, the
same approach would not work with the tensile or pneumatic assemblies, since in
these cases the material properties and acting forces could not be easily scaled
down while exhibiting the same structural behaviours.

The exploration of pneumatic and tensile structure not only gives students the
ability to simulate structural behaviour and derive unique forms but also helps
to explain the principles and science behind calculations. In the case of tensile
and pneumatic structures, quad-based surface meshes, familiar to students from
three-dimensional modelling software, are used as “virtual” spring nets (exempli-
fying Hooke’s laws) to simulate tensile behaviour and derive optimized surfaces.
In these spring-net models, mesh edges are interpreted as springs, while vertexes are points where forces such as gravity are applied. The displacement of vertexes is controlled by a spring’s ability to expand, the tendency to return to its resting position, and the amount of physical force (load) applied to individual points. Once all loads and spring properties are defined, the surface is going through self-normalizing reiterations and ultimately settles down in the optimized target tension state. By controlling the initial and the resting spring (edge) lengths, we can simulate both stretching and contracting surfaces. This approach can be used effectively for tensile structures as well as for geometries that wrap around a group of objects and produce a surface with a minimum volume.

9. What is Being Learned from Digital Versus Physical Mock-ups?

With today’s generation of students, who often 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 students to understand the translation process of their ideas from the digital to the physical. I have observed with many students the perception that once design is modelled in a three-dimensional virtual environment, it is perceived as fully resolved. If it can exist in a three-dimensional model, it also has the right to exist in a physical setting. 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 designs or pneumatic structures, 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 firsthand 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.
Similarly, material choices become critical when considering both types of structures, pneumatic and kinetic. In pneumatic designs, the weight of the material had to be offset by the applied pressure and the quality of seam welds. Designs had to strike a fine balance between a membrane (skin) and the underlying skeleton, particularly in the air-inflated pneumatic structures that are supported by pressurized air within an inflated structural core. In the kinetic designs, the material-to-material interactions – friction – and fatigue become critical design drivers. Repetitive movements, rotational and lateral, quickly affect the material integrity and connections when applied for a longer period of time. This became evident in a number of projects that used wood-on-wood assemblies, where even a change in the air humidity would affect component movements. While most of the mock-ups were realized with hand tools and traditional woodshop machinery, kinetic designs had to resort to laser cutting of the individual components. This in turn predefined the range of possible materials, with acrylic glass being the most effective from the standpoint of material durability and appearance.

10. Summary

While each case study project tackled a particular structural system with its own, often narrow, characteristics and concerns, as a group students dealt with a number of important design issues that start to permeate into everyday architectural practices. Considerations of efficient material usage, or designing for kinetic and adaptive structures, are just examples of challenges and opportunities associated with current practices. Probably the most important lesson came from the student hands-on involvement in creating-making their own designs. It is rare in the course of architectural education that students have an opportunity to test and realize their own creative ideas, albeit in an abbreviated mock-up-sized magnitude. The built mock-ups in most cases differed from the original ideas. While building them, students went through a give-and-take process of negotiating initial design aspirations against material and structural considerations. This back-and-forth process, culminating with building a physical mock-up, provided students with an important feedback mechanism regarding their often digitally idealized creative thinking. I found that building physical and digital mock-ups, and reconciling emerging differences, effectively situated design challenges and provided vehicles for their resolution.

Endnotes

1. As evident in Filippo Brunelleschi’s work, among others.
2. One of the areas where physics-based form finding is used in architecture is in the design of tensile structures such as tents and cable nets as well as pneumatic structures. Small-scale models using canvas, chains (Antoni Gaudí), and soap films (Frei Otto) have been used to derive these
surfaces, since they approximate minimal-tension surfaces. However, measurements and controls of these models can be difficult, in addition to material and scale differences that make any measurements only partially useful.

3. The reason for “pre-cooking” the simulation – starting with the geometry that is close to a final pneumatic model – was to minimize time and avoid simulation artefacts. In some cases when optimizing more extreme shapes, such as a highly wrinkled form, even after a relatively long simulation time there were still residual elements of the original wrinkles in a simulated geometry.

References


