TACTILE EXPERIMENTAL PARAMETRICS

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ABSTRACT: Parametric modeling and assembly of curved surfaces can be difficult for students to grasp due to complex computational workflows that rely upon higher mathematics. Using readily available materials and 3D printed components, a kit for parametric curved surfaces can initiate students into this field of contemporary design using a tactile approach. Software templates then enable the students to create a digital model of their initial physical model. The paper presents an example kit for *Tactile Experimental Parametrics*. It describes the concept, the parametric models of the fittings, the printing process and tools, the parametric modeling of the assemblies, and example designs produced by the students. The software tool for modeling was Autodesk Revit, and the 3D printing was done with an XYZ Print desktop printer. Workshops were conducted at Harbin Institute of Technology with students in the upper levels of the architecture program.

KEYWORDS: parametric, modeling, toy, learning, workshop

INTRODUCTION

Arguably no longer a trend, the modeling and fabrication of curved surfaces has become a common part of many architectural curricula and a response by architects that is no longer surprising. However, many students have difficulty grasping concepts that are critical to the craft behind designing and manufacturing such surfaces and may have similar difficulty conceptualizing a form. Working in a digital medium with unfamiliar ideas is an abstract activity that can lead to creative blockage. The chosen solution is often to vary a design that a student has seen before or use a "canned" script or process with predictable results or predictably unpredictable results (Doyle and Senske 2016). There can be a tendency to stop at an elementary solution that is quite beautiful, but does not exemplify much creativity. Even a commercially designed, massive structure such as the Metropol Parasol in Seville is conceptually little more than a gargantuan studio project using a wooden egg-crate assembly. There is a need to help students move beyond elementary and rote solutions, and develop "deep learning" that enables them to apply fundamental concepts in new and novel situations (Doyle and Senske 2016).

There are lessons that are best learned in physical exploration just as there are lessons that are best learned in digital exploration. However, by combining the two modes of exploration, there is an opportunity to "bridge the divide between digital and tactile design" (Snoonian and Cuff 2001). Much of the digital fabrication pedagogy that has arisen in the last twenty years has implicitly adopted this agenda, although often without a clearly stated pedagogical objective. Nevertheless, "Design education and digital technology education continue to be seen as separate loci of learning, separated by pedagogical gaps and teaching mindsets" (Doyle and Senske 2016, 192). The investigation described in this paper explores design of curved surfaces through tactile experimentation with a veritable physical toy to reveal fundamental issues and a range of possibilities. A digital representation of the toy then reinforces how the physical can be represented as a digital model. The use of digital tools of parametric modeling and 3D printing are necessary to produce the instruments of the investigation, but are not the investigation itself. The goal of the investigation is not to make something with "wow" appeal in an academic setting, but to help students to understand essential concepts in designing and building curved surfaces at an architectural scale.

A secondary motive is to increase students' knowledge of Building Information Modeling and specifically Autodesk Revit for creating digital models of curved surfaces and fabricating them.

1.0 CONCEPTUALIZATION

The spline is a key concept in describing a free-form curve to the computer, and the skin made by sweeping and blending splines is the recurring method for describing a surface. Nevertheless, when such an architectural idea is elaborated into something at the scale of a building, the smooth, liquid forms must be fractured and faceted, usually into flat or singly curved panels, and then supported with fittings, struts, and columns in assemblies of primary, secondary, tertiary, and even quaternary structural elements. Explaining the set of parts and elements and teaching students to design them is a challenge to their patience. Students often do not recognize or acknowledge the devotion, intellectual effort, and time that is necessary to design and fabricate a complex form. Teaching the concepts and techniques using didactic methods and tutorials can take many sessions and consequently the ability to model curved surfaces may be perceived as a specialization for an elite few designers. Many students give up and resort to conventional and "canned" solutions.

Students may also fail to finish fabrication projects because they have not learned fundamental principles of manufacture and assembly. The precision necessary in fabricating curved surfaces is a challenge for many students who are accustomed to building cardboard models where they can cut to fit. The notions of tolerances, use of physical connections rather than glue, impact of thickness of materials, and exploitation of deformation of a material are some of the tangible, physical realities that are difficult to grasp in a purely digital medium. Students often build a physical prototype that fails before they can respect the principles that govern design and manufacture.

1.1. Building toys

The insight of this research derives from personal childhood experiences. A few decades ago, digital or virtual play was non-existent but tactile play was omnipresent. Children had many building toys:

- Wooden blocks
- Tinker Toys
- Lincoln Logs
- Meccano sets
- Erector sets
- Lego blocks
- Girder and Panel sets
- Plastic kits of ships, airplanes, military vehicles, automobiles
- Balsa and tissue airplane models

These toys taught basic ideas in masonry, log, and steel construction, and introduced hierarchical assemblies involving foundations, columns, beams, plates, joists, trusses, shear walls, panels, fasteners and connectors. They involved press fits, mechanical fasteners such as nuts and bolts, and glued joints. However, none of them (except the plastic kits and the balsa and tissue airplanes which constrained modeling to a single instance) allowed for creating complex, doubly curved surfaces. Although Tinker Toys impose a hexagonal geometry, most of the tools rely upon rectangular geometry with a distinct dimensional module. One may criticize these childhood toys for normalizing design ideation into a presumption of rectangular forms. A toy for curved surfaces could be an interesting addition to the panoply of building toys, subtly presenting and integrating different concepts and patterns that are particularly relevant to contemporary architecture.

1.2. Toys first

Teaching fundamental concepts in curved surfaces using a building kit turns the current digital fabrication process on its head. First, students would use the kit to build something with their hands. In theory, this tactile activity will actuate their experience, heighten their perception, whet their appetites for learning, and ground their memory. This is followed by digital modeling to represent the assembled toy, engaging abstract thinking as well as simple acquisition of skill with the software. From the digital model of the toy, the student is challenged to design something new by employing the newly learned principles and techniques in creative ways. Production of a final physical assembly from the digital model closes the loop and engages the students as designers to create new surfaces, panels, connectors, and structural elements.

The use of a toy encourages experimental play while reinforcing concepts and skills through a combination of tactile and digital exercises. The process leads inevitably to an early success, as the student assembles the toy to make something intentional and in some ways surprising. We use the term Tactile Experimental Parametrics to describe "toys first" learning that sequences playing with a toy, modeling it with the computer, producing a new custom toy, and repeating to refine the design idea.

1.3. Devising the toy kit

The conceptualization of this experiment involved a search for commonly available materials that could be appropriated for use in a building kit toy. A pegboard is a "found" material that establishes a field of datum points, while dowels provide the third dimension to locate points in 3D space. Representing the spline requires a linear material with flexibility to accept changes in shape yet stiffness to produce curvature. After trying string, copper wire, grass trimmer string, and other materials, 1/4" irrigation tubing proved to have the proper material characteristics for representing a spline in 3D physical space. Paper, cardboard or other readily available and easily cut materials can be used for panels. The connectors are the critical part of the system and join the simple linear and planar materials to make complex forms. 3D printing of connectors could enable the toy to work.
Joker Kit is a first experiment in using this learning method. It consists of irrigation tubing, dowels, pegboard, fittings,

and playing cards. Two kinds of 3D printed fittings are provided: a connector to clip a length of tubing to a support dowel, and a connector to attach a card to the tubing. Dowels may be cut to various lengths and inserted into the holes in the pegboard. The playing cards are another found material that is a module with an attractive stiffness in a comfortable size scaled to fingers. They may be used whole or may be cut with scissors to special shapes. The fittings provide overlap and slack to allow the tubing to be moved up and down and the cards to be supported even after sliding in and out. Panels can be applied using overlaps and gaps, or cut by hand or with a laser cutter to precise dimensions.

Producing the kit required designing the connectors and cutting other elements to appropriate sizes for a desktop toy. The pegboard was cut to 45 cm by 61 cm (18 inches by 24 inches) as a reasonable field for building a modest model. The dowels were cut to various lengths ranging from 7.62 cm to 30.48 cm (3 inches to 12 inches) to allow designers to position 3D points at various heights. Slots cut into the ends in a way similar to those in a Tinker Toy dowel facilitate a tight press fit into the holes in the pegboard or into the connector at the top of the dowel.

Figure 1: Joker kit parts.

2.0. MODELING COMPONENTS

Printing the two connectors requires modeling the connectors in a 3D modeling environment. Anticipating use of press fits that can resist modest force to pull the two elements apart, it was advantageous to use a parametric constraint-modeling tool to enable experimentation with dimensions. Autodesk Revit has adequate capabilities to support modeling the connectors and was used for modeling. Many other tools, such as McNeel Rhino, Autodesk 3D Studio, or Autodesk AutoCAD, could be used.

2.1. Dowel cap

The connector to join the dowel to the tubing is referred to as the “dowel cap”. It is a cylinder with a void cylinder subtracted from one end to form a recess to receive the dowel. Both cylinders are parameterized to allow experimentation with the tightness of the fit of the dowel into the cap and the strength of the wall of the hollow cylinder. The top of the cap is a hook to hold the tubing in place. It also is parameterized along several dimensions. The opening of the hook was varied to reach a comfortable press fit of the tubing into the hook, relying on deformation of the tubing to force it into place and then rebound of the tubing so that it does not easily pop out of position. The thickness of the hook in both directions affects the cross section to allow control of the strength of the hook. Too little material and it will break easily. Too much material and the effect is coarse and the use of materials is inefficient. The opening of the hook must have sufficient slack to allow the tubing to pass through the hook in an upward or downward direction.

2.2. Panel connector

The connector between the tubing and the playing cards is referred to as the “panel connector”. Similar to the dowel cap, the amount of material and size of the openings must allow press fits to the tubing and to the playing cards. A slight clamping action is desirable to hold the playing cards. Also, the panel connector is designed to allow the panels to slide close to the tubing or away from the tubing to account for the variability in size of the panels necessary for suggesting a curved surface.

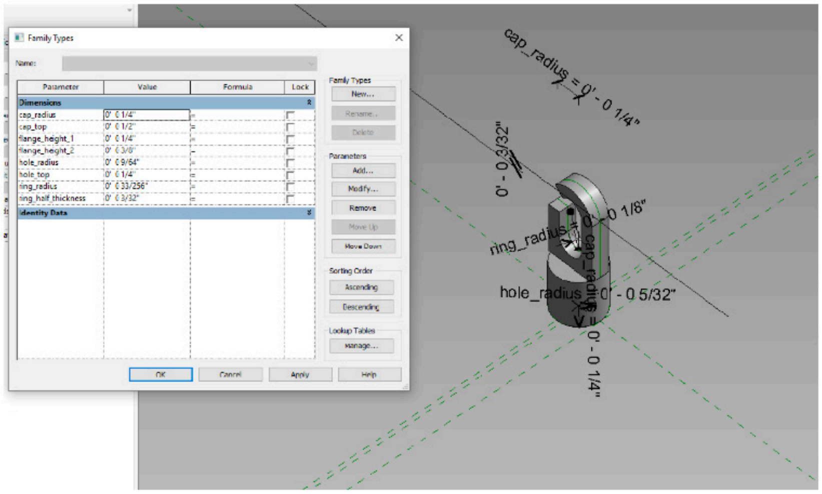

Figure 2: Dowel cap.

2.3. Production
The dowel cap family and the panel connector family were placed into separate project files. Each was then saved as an ACIS file, imported into AutoCAD and then saved as an STL file. Alternatively, an addin for Revit is available for saving an STL file directly from Revit. The STL file was then imported multiple times into the 3D printing software, in this case, XYZ Print. Printing two dozen connectors required about twelve hours.

A designer should understand that quality of modeling affects the ability to print the STL file. A fundamental concept is the physical reality that two solids cannot exist in the same place at the same time. Sloppy modeling may intersect various solids, producing something that looks right but is physically impossible. An STL file may then require extensive repair to produce a printable representation. If the user takes the time to subtract volumes where two solids intersect, the model can be perfect and require no repair in the STL representation. The solid modeling approach provided in Revit encourages creation of high quality models that make perfect STL files. Neither of these connectors required any repair to the STL files to permit printing.

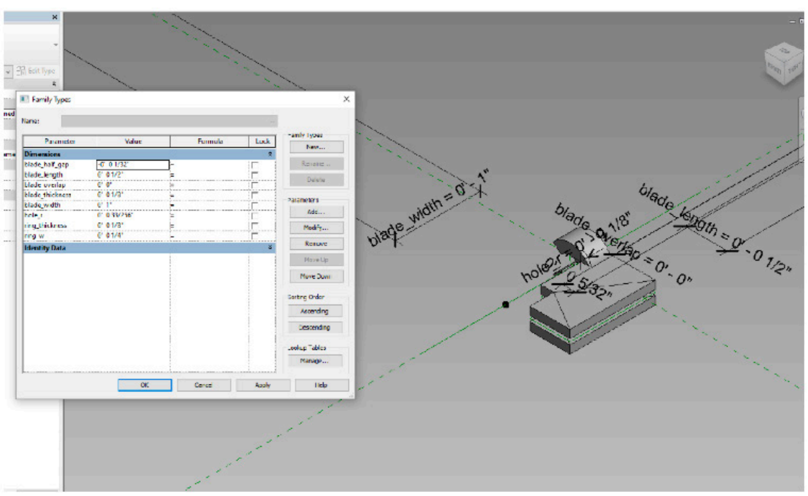

Figure 3: Panel connector.

2.4. Playing with the toy
Putting together toy assemblies proved irresistible and the kit was tested by building modest assemblies. Dowels are easily cut to new lengths. Tubing is easily to cut to new lengths and to shape to new forms. Playing cards may be cut to new shapes. No glue is required, allowing the model to be reconfigured rapidly and the designer to explore alternative design ideas.

Figure 4: Test Joker assembly.

3.0. DIGITAL MODELING OF ASSEMBLIES

To facilitate learning how the concepts translate into the abstract world of digital modeling, the second stage of the assignment requires students to model the physical model with the digital tool. The process of digital modeling was worked out to provide students with step-by-step instructions. In a simplistic approach, each element in the toy can be modeled as an element in the digital tool (Autodesk Revit in the case of this experiment). However, there is no need for the digital model to be identical to the toy assembly. Instead it can inspire a more sophisticated and refined design that overcomes some of the limitations of the toy and adapts it for the full size of an architectural work.

3.1. Simplistic model

For the simplistic approach, the several components are each modeled as families in Revit. The pegboard is easily modeled as a Generic Model rectangular extrusion with a grid of holes subtracted. Dowels are modeled as an extruded Generic Model family with a parameter to determine the height. The dowel cap family can be reused from the one used to produce the 3D prints, as can the panel connector family. Dowel locations on the pegboard and dowel lengths in the physical model determine points in 3D space that control splines. The tubing can be modeled as a Generic Model Adaptive family with a line controlled by adaptive points and a cross section of the tube swept along the line. The playing cards can be modeled as simple extrusions of the rounded rectangle shape. If the card were modeled using the Generic model family, it could only take on a rigid planar form. By using the Generic Model Pattern Based family, the card will tolerate warping out of plane, behavior that is more accurate to the playing card or to real-world panels.

This simplistic model makes use of a variety of Revit families with various behaviors. The Generic Model family provides for simple parametric modeling of dimensions using a single placement point. The dowel cap family and the panel connector family are mildly complex Generic Model components. The Generic Model Adaptive family provides for multiple placement points in non-planar 3D space. The Generic model Pattern Based provides adaptive behavior constrained to a standard pattern, in this case a warped rectangle.

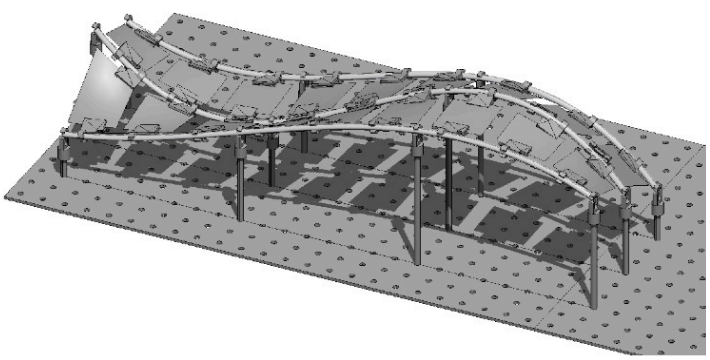

Figure 5: Example of test Joker assembly modelled using Revit.

3.1. Abstract model of architecture

If the toy model is recognized to be an abstraction or study for determining some more refined design, then modeling the assembly takes on a more creative dimension. The pegboard and dowels can be understood as merely the expedient pieces for placing points in 3D space. A different foundation can be designed. The tubing is merely an expedient physical embodiment of an abstract spline curve. To ease construction, it could be rationalized into straight segments or circular arc segments. The connectors, likewise are merely toy parts that do not need to correspond to the assembly in a building. The playing cards are also expedient panels used to suggest the surface. Panels in a real building may need to take on unique triangular or irregular shapes.

Given this understanding of the toy assembly, as merely an abstract model of an architectural built surface, digital modeling can proceed in new directions. The splines can be blended to make a surface. The surface may be divided in various ways, allowing for faceting of the surface to be achieved in various ways. Mullions, struts, stays, beams, girders, and columns may be designed to make something realistic. The next iteration of physical modeling can produce a new custom kit that has greater fidelity to the ultimate building, but is still made of plastic, wood, acrylic and other model-building materials. Ultimately, the BIM representation can drive production of steel, glass, aluminum, and other construction materials that could be used in full-size mock-ups or fabricating the components of an actual building.

3.2. Facet production

- As the student explores tessellation and faceting of a surface, production of irregular panels is a challenge. Autodesk Revit can be used to produce the panel cut sheets. The process is clumsy because it relies on a long list of procedures, but it does not involve programming or scripting:
- Label the panels with an identifier;
- Extract key dimensions from the panel family using reporting parameters;
- Produce a schedule of the panel dimensions and labels;
- Save the schedule as a CSV file;
- Using the CSV file, produce a spreadsheet file in the proper format for Revit Lookup tables;
- Produce a flattened panel family that reproduces a labeled panel using parametric dimensions;
- Drive the flattened panel family from the spreadsheet of dimensions using a Lookup table;
- Place the flattened panels in a new Revit project on a plan view, varying the label to look up each set of dimensions;
- Add the view to a sheet in Revit.
- Save the sheet as a DWG file;
- Send the DWG file to a laser cutter, 3-axis milling machine, or water jet cutter.

4.0. WORKSHOP

The method was tested in a ten-day workshop in May 2016 at the Harbin Institute of Technology. A group of students were selected from upper level undergraduate and graduate students in architecture programs. Students were already adept with using Revit, but had little or no experience with adaptive components and parametric form making.

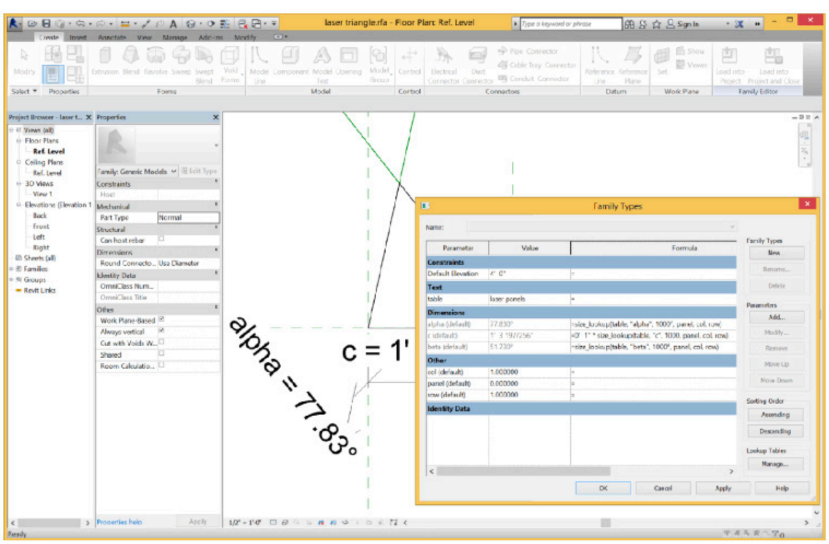

Figure 6: Use of lookup table to control parameters of a panel family.

The first class period focused on an exercise to use the Joker kit to create a physical model of an architectural curved surface. Subsequent class periods provided review and discussion of the forms and instruction in how to model them in Revit. Students were then shown additional Revit commands for dividing surfaces with patterns, building adaptive components for connectors and panels, and production with 3D printing and laser cutters. They were challenged to design a public canopy, such as a train station shed, a bus depot, or a public park covering.

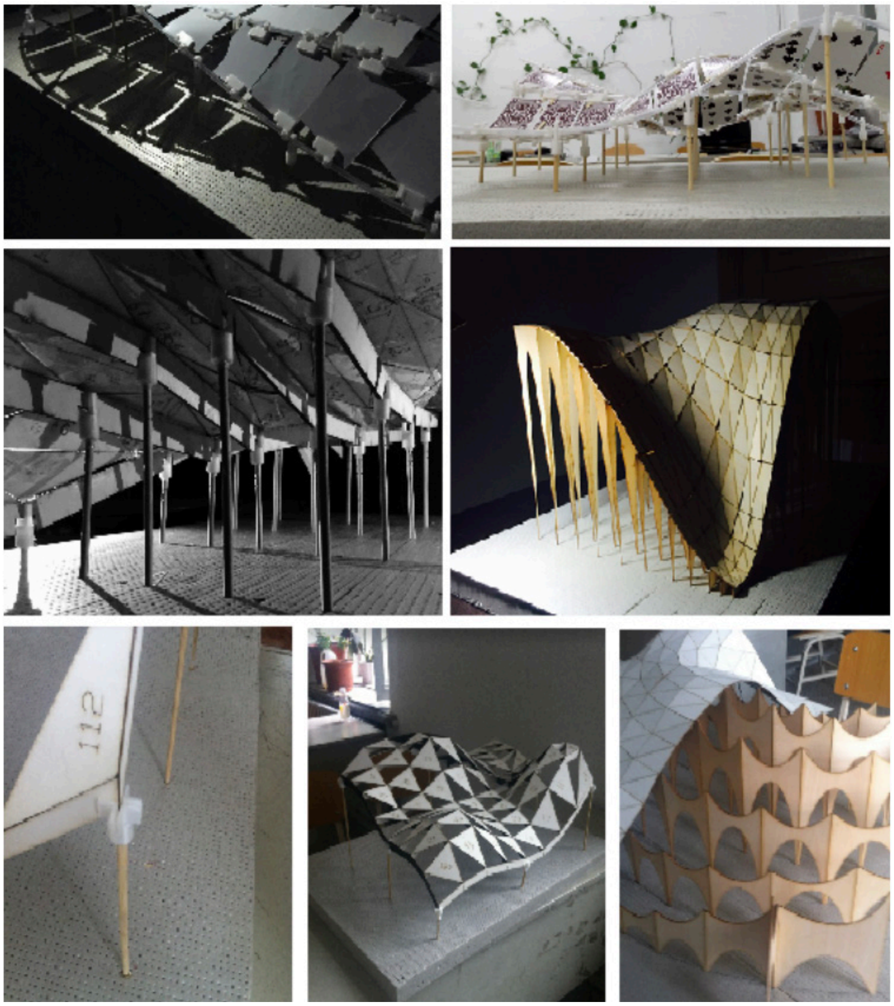

Figure 7: Products of the workshop

Students' products demonstrate success in using the Joker kit, and some degree of inventiveness in the original composition. The student teams used conventional triangular faceting for surfaces, but used a variety of support systems, including concentric bulkheads, beams with finger-like facet supports, and curved beams. One team modified the dowel cap by physically cutting it to a new shape, while another team redesigned the cap to support rectangular beams.

CONCLUSION

While the conduct of a single workshop is certainly not conclusive evidence in support of the method, it suggests that the exercise is at least adequately described for implementation, with promising pilot study results. Tactile Experimental Parametrics may not only aid a designer in thinking about the specifics of an assembly and the contours of a structural shell, it may also help a student to understand concepts in mathematics, form, and modeling. Tactile Experimental Parametrics helps students break down complex physical forms into designable and buildable assemblies. The lessons learned cluster into three categories:

Mathematical and geometric concepts

- Cartesian field in 3 dimensions (the pegboard and dowels)
- 3D splines and control points (the dowels and irrigation tubing)

- Blended surfaces (the playing cards between the tubing)
- Surface normals (pins on the playing cards)
- Relative coordinates

Materials and fabrication

- Tolerances (the connectors)
- Panel deformation (the playing cards)
- Friction fits and material deformation (the connectors)
- Flattening facets (the Revit workflow using Lookup tables)

Architecture and assembly

- Hierarchical structural systems to collect loads and transmit them (the Joker kit)
- Adaptive points and elements (the Revit model of the Joker kit assembly)
- Inventing and managing a complex workflow (assembling a Joker model, flattening facets, devising a new kit, designing an architectural curved surface)

By engaging tactile play, the Tactile Experimental Parametrics is intended to ground the concepts, make them tangible rather than abstract, and reinforce memory. The approach may be effective in other levels of education for teaching mathematics and geometry, including kindergarten and primary school, secondary school, as well as college-level instruction.

The exercise could be executed using other digital tools or could provide other lessons in modeling, fabrication and assembly. Other 3D surfacing paradigms could be implemented, such as NURBS, constructive solid geometry, mesh modeling, and topological mesh modeling. As executed, the exercise had a secondary objective of fostering facility and confidence with a BIM tool. It effectively conveyed to students that Autodesk Revit is capable of representing complex, curvilinear shapes that may be easily modeled through a parametric approach.

Bloom's taxonomy has been suggested as a useful way for architectural educators to structure courses for identifying learning objectives (Doyle and Sensek 2016). The Joker exercise works through the entire Bloom's taxonomy of learning. Basic concepts are presented as discrete and abstract knowledge. Comprehension is aided through a tactile exercise of assembling the Joker kit. Application comes from modeling the physical assembly as a Revit model. Analysis and evaluation occurs when students assess the Joker kit and Revit model for adequacy in an original design. Creation is the final outcome of designing and fabricating an architectural work.

It has been suggested that designing with computer tools has become so common and normal that our era should be seen as a "post-digital" era (Kolarevic 2008). However, there is danger in the post-digital situation that cultural forgetfulness discards the information and knowledge that enabled us to arrive at this point. The "digital native" may not understand the tools that are employed with such facile skill, and thus be unable to produce new ones (Doyle and Sensek 2014). This experiment represents a "post-digital" effort to get back to understanding the roots of computational design. The design of the curved surface is not an end in itself or an expression of the delight in using new tools to make new things, but a carefully formulated exercise meant to foster and reinforce learning of targeted architectural knowledge. This investigation is essentially a "post-digital" study that treats the digital as both instrument of study and focus of study, but not the end of study (Swackhamer 2011). Learning to design with computers is inseparable from learning to design in the 21st century.

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