Physical Modeling: the Convergence of Cutting-edge Technologies and Miniature Tooling

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When Rapid Prototyping and CAD/CAM technologies (including CNC and Laser Cutting) became affordable, ten years ago or so, their reception within model-making circles turned from positive to disappointing because of their incomplete adaptability to the making of architectural objects. Then it was discovered, just few years later, that many modeling details can only be worked out through the use of specific materials, accessories and miniature tools which neither fall under the CNC, Laser or Rapid Prototyping headings. This new situation has implied, among other things, that the status of the model is to be defined in terms of a convergence of particular technological possibilities. Using two specific models as examples, the present article will debate this convergence, which is now allowing a smooth and fluid interaction between several model-making techniques. The tendency of model-making to move closer to the real act of building will also be highlighted.
I. INTRODUCTION

From the standpoint of representation, and despite the advent of computer graphics and animation, the architectural model has persisted in being a privileged way of expressing architectural intentions. Architectural firms have continued using this mode of representation because of the irresistible iconic relation between the model and the building on the one hand, and the intimacy witnessed through this association on the other. Because the physical model has been traditionally made manually (it often takes several hours to interpret, visualize, hand-cut and build the information conveyed by plans and technical drawings), and because of the advent of digital technology and the subsequent connotations of speed, there has been a tendency to equate model-making with slowness, tediousness and inflexibility. The traditional process is time-consuming, indeed, and is generally lacking in precision. This has contributed to the relegation of (physical) model-making to a second position in the debates dealing with architectural representation in the digital age, despite the fact that several international architectural firms, such as the often-quoted Frank Gehry’s studio in California, have successfully pushed model making to the forefront of their design strategies and methods. But since the last ten years or so, some researchers in the architectural computing area started to point to the emergence of new cutting-edge technologies that could be of great relevance to the making of both models and buildings. The publications by Rawson [1], Novitski [2], Eliassen [3], Chaszar [4] and Kenzari [5-6-7] are worth mentioning in this respect.

The advances made in the Rapid Prototyping domain (Stereo lithography Apparatus (SLA), Selective Laser Sintering (SLS), Fused deposition modeling (FDM), Laminated object manufacturing (LOM), 3-D Printing (3DP) and in CAD/CAM technologies (including CNC routing, Laser/Flame/Plasma/Water cutting) have offered designers the great privilege of building physical objects directly and automatically from computer files, with the explicit implications of speed, precision and flexibility [1]. The useful translation and conversion of digital data into a setting favorable to the making of artifacts, at whatever scale, and with a minim manual intervention suggests that digital, CAD/CAM and Rapid Prototyping Technologies are now becoming complementary domains of expertise, all combined to crystallize architectural design intentions in the most efficient fashion. Slowly, the strategies by which we teach and conceptualize architecture at large are becoming complex, efficient, and multi-faced. The gap between the digital and the real is shrinking. Of course some of these technologies are expensive, others are more affordable. Some could be used for the making of both models and buildings; others are more efficient at the manufacturing of small size objects only. Some could be installed inside office spaces, others on bigger construction sites and factories. Whatever the case, through this web of new technologies, where the digital intermingles with
CAD-CAM and Rapid Prototyping, the physical visualization and crystallization of the architectural idea is becoming a smooth process, rather than a single operation as the case used to be in the traditional atelier.

Notwithstanding the advantages of these new technologies mentioned, there are modeling details that can only be solved through the use of specialized materials, accessories and miniature tools which neither fall under the CNC, laser or rapid prototyping categories, but complement them. This point is the central thesis of the present paper. To develop it further let us first examine the most often-used cutting technologies, introduce miniature tooling, then conclude with a reflection on their convergence.

2. PHYSICAL MODELING AND NEW TECHNOLOGIES

2.1. Rapid prototyping

Rapid prototyping (RP) lets designers build physical entities directly and automatically from 3-D computer models. A dozen varieties of rapid-prototyping devices create models by building up thin layers of a particular material (Figure 1). They all require 3-D CAD data translated to the STL format, named after stereolithography, the original rapid-prototyping technology. STL files are most easily created from 3-D solid modelers. Rapid prototyping is common in the design of automobiles and consumer products. Industrial designers in these fields routinely use 3-D solids-modeling systems such as Pro/Engineer and SolidWorks to describe objects that curve in three dimensions. To architects who typically work in 2-D to design buildings, 3-D modeling may seem overtly complicated. But 3-D modeling is virtually mandatory for creating good STL files. Architects willing to learn these 3-D modeling systems can take advantage of rapid-prototyping technologies to build physical models with their CAD data.

Figure 1 Model made on a Z400 Zcorp rapid prototype 3D printer machine (courtesy by Global Information Technology, Dubai.)
The oldest and most common system is stereo lithography apparatus (SLA) from 3D systems Inc. There are several SLA models, which vary in size, speed, and cost. With this technology, a laser beam moves through a vat of ultraviolet-sensitive liquid polymer, following the contours of the model’s floor plan. When the beam hits the liquids, a thin layer is solidified. Then the model is lowered slightly within the vat, and the laser produces the next layer. Because the layers are built from the bottom up, the CAD models must provide temporary supports for roof overhangs and similar geometries. Breaking off the supports after construction can potentially damage the model. Toxic fumes from SLA make it unsuitable for an office environment. The process, however, affords great precision and strength even in delicacy shaped objects. [2]

There are similar processes that could be investigated as well, such as: Selective laser sintering (SLS), developed by DTM Corp; Fused deposition modeling, or FDM, sold by Stratasys Inc; Laminated object manufacturing (LOM), from Helisys Inc; and 3-D Printing (3DP), invented at the Massachusetts Institute of Technology and commercialized by Z-Corp. [2]

Rapid prototyping makes models with complex geometries more affordable than if constructed using traditional means. As a general remark the cost of this technology is no longer a barrier, and most architects don’t realize how dramatically prices have dropped; a model that fits in a six-inch cube costs around $100. RP machines have a wide range of options, capabilities and prices. Presently, 15 companies offer more than 50 different systems. With advertised prices of $45,000 to $800,000, the purchase of the equipment does not present a hidden cost; however, support of the machines and long-term requirements can present a few surprises. A more serious barrier is the investment of time and training in conventional software that architects have made. In most cases, a 3-D model developed from 2-D drawings will make a poor STL file. Only time and experience will show the most convenient way to address this hurdle. [2]

2.2. CNC and laser cutting

In its simplest form, CAD-CAM is a way for a machine operator to cause the cutting of a surface. The cutting tool follows a certain path controlled by a computer. The size of the worktable limits the size that can be cut. Parts that are cut are later attached, mainly using chloroform glue.

CNC routing machines work by translating programmed instruction coordinates into precision motion along the path specified. The CNC router uses a tool to machine that path to produce the desired profile. This allows a programmer to write a part program and route many identical parts on a given day, then resume that same program weeks or months later. CNC routers are incredibly fast and have powerful spindles capable of routing and machining very thick sections of solid wood and other materials. CNC routers are even used in manufacturing parts from non-ferrous metals such
The cutting process starts with a design drawn in a CAD or other graphics programs. These drawings are generally 2-D, but include multiple layers used to separate features of the design or cutting operations (such as a "Cut" layer and an "Engrave" layer).

Laser cutting is an excellent method of delivering a very precise controlled spot of heat just where it is needed. Laser produces a significant amount of energy in an extremely small area (as small as .003"). This focused energy leaves its mark by heating, melting, burning or vaporizing away the top layer of the object. Distortion is minimum.

There are other promising technologies such as: Flame cutting, Plasma cutting, and water cutting. In Flame Cutting, also-known as oxy-fuel cutting, flame can penetrate up to 160mm thick. Fast, cheap, accurate technology, it is used mainly in shipbuilding and automobile factories for cutting steel plates. In Plasma Cutting an electric arc is struck between the cutter head and the work piece, which melts locally, and is then blown away by a powerful stream of inert gas; 50mm thick materials can be cut. This technology is more accurate than flame cutting. The newest cutting method is water cutting. Water carrying abrasive under extremely high pressure (55,000 bar) is discharged against the work through a tiny nozzle. A very precise and smooth surface is engendered. It is yet to be seen how these technologies can be appropriated for model-making purposes. [1]

3. MINIATURE TOOLING

Miniature tools are not, in themselves, parts of the cutting-edge technologies mentioned above, of course. But, like parasites, they play a major role as parallel elements. Whether powered by an electrical motor or activated manually, they all tend to be of a relatively small size, and are useful to accomplish very specific tasks. One instance of this fact is, for example, the modeling of tensile structures [7]. Although a typical tensile structure would require the intervention of high tech cutting technologies like CNC and laser cutting at the beginning of the cutting process, it still needs parallel techniques that include the implementation of specialized stretchable material, swivels, cables, eyelets, etc, with the entailed technical expertise involved. The relevance of these miniature tools is their ability not only to help us make 3-D forms that are made from 2-D aggregates but to fill those modeling gaps that could not be performed by the cutting-edge technological devices. At the moment, the making of a given model within the CAD/CAM domain is not one single operation, but a process of designing, cutting, assembling and finishing many parts. Even the most promising modeling technologies, namely rapid-prototyping and 3-D printing, cannot by themselves secure all the modeling requirements that are
specific to the making of an architectural object. A 3-D printed model, for example, does not lend itself to its being “edited” and therefore becomes a rigid, inflexible object. The impossibility (and undesirability) of a universal cutting-edge technology, therefore, makes the role of the miniature tools an urgency so much so that the interface between cutting-edge technologies and miniature tooling is becoming a converging process and an integrated continuum.

Before going any further, let us first introduce some of these miniature tools that we have been using here at our advanced model-making laboratory. The list below is selective, of course, and is presented here in relation to the modeling questions debated in this paper, but there are literally hundreds of miniature tools available in the market and which could be visited on several specific websites.

3.1. Microlux drill press

Microlux Drill Presses have all the quality features of regular drill presses. Here is an affordable drill press designed and sized for small precision work. No more working with cumbersome, oversized drill presses, and no more mistakes from using inaccurate, hand held drills. Plus, one can select the right speed for the job in seconds. These minuscule drills do prevent jagged holes in wood from a speed too slow, protect against overheated plastic from a speed too fast. And drilling in steel, brass or any metal is also handy and easy. The high torque motor will drill a 1/4 inch hole through 1/4 inch brass quickly and easily and even deeper holes in wood, plastic and other soft materials (Figure 2).

3.2. “Third hands”

“Third hand” keeps the modeler’s hands free for soldering, gluing, positioning, while work is held firmly at any angle required. This uncanny tool has 3 alligator-type spring clamps mounted in ball joints for flexibility. Since the modeler performs several tasks at the same time, the ‘third hand’ with its three clamps plays the role of an assistant which holds several parts of the model together, thus letting free hands for the modeler to glue, fix, drill or tape these same parts or other parts of the model (Figure 3).
3.3. Dobson-miter saws

“Dobson-miter”: finest miniature tool for making perfect angle cuts in wood, plastic and soft metal. Cuts are adjustable in 1 degree increments with a range of 65 degrees on each side of 90 degrees. Blade holder keeps blade absolutely perpendicular to the base, assuring straight and accurate cuts (Figure 4).

3.4. Manual eyeleting machine

Eyeleting is the process of reinforcing punched holes with plastic or metal grommets. This work is generally done by firms specializing in calendar, leather work, etc. Manual eyeleting machines are designed to fix eyelets to various materials with the need to pre-punch holes. These systems are widely used in the shoe, leather, plastics, cardboard, packaging, medical, automotive and aerospace industries. These machines can fix eyelets, sail eyelets and grommets to various materials. In addition, these machines can be equipped with an automatic eyelet feeding system, adjustable tables and guides, optical projector for centering insertion point, and can generate a flat or star round edge according to specific needs and eyelet type (Figure 5).
3.5. Beveling Varga2 Machine

Beveling is the removal of sharp edges on workpieces, boards (e.g. plexiglass sheets) by producing a so-called bevel, that is a slant across the edge. The production, by a machine or otherwise, of a sloping edge on two separate plastic sheets is needed if one wishes to obtain a clean, straight surface line upon joining those two sheets at a given angle (generally 90 degrees). In the lab we use the Bevel Appliance Varga2, which is a relatively new appliance, to bevel plastic edges of all kinds. The equipment is a carbide-tipped saw blade (diameter 120 x 1.7 mm), a V-guide (280 mm), a depth regulator (4.5 mm) and a suction device for sawdust. The required depth is regulated by means of a simple knurled-head screw. Dust is removed so that the place of work always remains clean (Figure 6).

4. PROCESS OF MAKING

To illustrate the combination of both cutting-edge technologies and miniature tooling, let us review the process of making two models made here at our advanced model-making lab (Figure 7 and 8). The first is a hypothetical building with façades and decorations cut with a laser cutter, but involving the use of several small machines. The second is a physical rendering of Jeddah Hajj Terminal, designed by Skidmore, Owings and Merrill (1978-82) partly cut on a CNC router, then completed with the assistance of many tiny devices. Whereas the first model shows the role of detailing in connection to fine wall textures, the second demonstrates the role of miniatures machinery and tools in the rendering of tensile structures.
4.1. Process of building model # 1

In the table below are few steps selected from the process of making the model #1 (Table 1). It is to be stressed that since we don't have a laser cutter here at the Department of Architectural Engineering, we had to hire the commercial services of a laser-cutting firm in Dubai. Given the expensive nature of this process, we limited ourselves to one single testing of this procedure.

4.2. Process of building model # 2

In the table below are few steps selected from the process of making model #2 (Table 2). The introduction of the jersey stretch as a major fabric in the...
making of tensile structures, with all the consequent detailing of eyeleting, sewing, attaching and stretching, has been the major contribution of this exercise. Hundreds of hours were literally spent to find the best fabric and the most suitable techniques to model tents and similar structures.

5. CONVERGENCE OF CUTTING-EDGE TECHNOLOGIES AND MINIATURE TOOLING

Traditionally, there has been little mode-making episodes that involved advanced technologies. But when cutting-edge technologies became affordable and familiar to architects and architecture schools alike, their application was somewhat disappointing because of their incomplete adaptability to the making of architectural objects. It was assumed, for example, that from a digital 3-D file, you could instantly and automatically get a physical manifestation of it by high-tech means no matter how complex the geometries involved were! This assumption was based on the first promises presented by 3-D printing and rapid-prototyping. But this

<table>
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<th>Table 2: Steps involved in the making of Model # 2.</th>
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<tr>
<td>Prepare model base</td>
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<tr>
<td>Apply wholes on rings</td>
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<tr>
<td>Weld rings around copper rods</td>
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<tr>
<td>Cut layout on CNC router, then mount rods</td>
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<tr>
<td>Position all rods on site</td>
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<td>Set the eyelets in the center of tents</td>
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<tr>
<td>Mount tents: use of pliers to stretch fabric</td>
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<td>Mount tents: use of cables and fishing swivels</td>
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<tr>
<td>Proceed with mounting of tents</td>
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<tr>
<td>Use of fishing wire to stretch tents from the central eyelets</td>
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<tr>
<td>Application of accessories and planes</td>
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<td>Final model</td>
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belief was doomed to yield some degree of frustration given the subtleties
of the architectural model. Unlike the manufacturing arena, architects do not produce a “prototype” that could be duplicated, but a singular object that does not tend to be repeated and which requires several steps in the process of its making and editing. This, among others things, entails that the making of a given model is not as straightforward and direct process as it was assumed. Reality has shown that there was no such a thing as an “architectural prototype” made by an “ideal machine.” So much was this first disappointment that many firms started re-selling their CNC routers and laser cutters to second-hand machine dealers.

But as this first wave of disappointments started to abate, especially for the last five years or so, miniature tooling has gained its place within the model-making lab along automated technologies. Such cohabitation is now allowing a smooth and fluid convergence between the two forms of model-making techniques. Of course, each technology plays a more specific role at a given modeling stage of the modeling process. And we may note a certain “inflection point” in the interaction between cutting-edge techniques and miniature tooling whereby the model-maker seems to rely heavily on the cutting-edge technology from the start of the modeling process until the first layers of the model are cut, then a more pronounced miniature tooling phase starts. The reason the uses of cutting-edge manipulations are highest at the beginning of the modeling process and tend to slow down and eventually come to a stop at the end-phases is dictated by particular modeling needs. Whereas cutting is done automatically by a router/laser cutter directly from a computer file at the start of the modeling process, more specific tasks such as assembling, fixing, editing, painting, finishing are performed later, with the help of miniature tools, once the 2-d aggregates have been already cut.

The consequence of this convergence of miniature tools and cutting-edge technologies implies that operations performed with the help of miniature tools somehow acquire, because of their place within the process of production, a digital connotation. When a given model is conceived, designed, cut, assembled and refined it has already gone through many steps, some of which are digital others are manual. These steps are so interconnected that the real attribute of each stage could be defined half way between the digital and the manual. For unlike the traditional way of making physical models whose possibility lays in the (linear) performance of certain routines with the help of precise physical tool (knife, cutter, cardboard), the current mode of making models implies a relation between the material (analogue) and the non-material (digital) that reveals itself as a dispersion of moves through a field of technologies. This new situation implies, among other things, that the relation between the physical (analogue) and the digital (immaterial) is not always “present” but potential. The status of the model cannot, therefore, be exclusively defined in terms of a machine, be it a router or a drill, but in terms of a conglomerate of
swings, appearances, interruptions and disappearances of particular
technological possibilities. Rather than looking at current model-making
routines as something that reside in the margins of the digital, there must
be a stress on the opposite, namely that they are an integral part of digital
thinking despite their stipulation of a manual/physical element.

The convention underpinning most discussions of digital thinking tend to
identify the technological with the electronic production/manipulation of
images. When it comes to the making of objects that require a cutting-edge
technology, the situation changes and the semantic dimension of the digital
somewhat starts gaining new connotations. The digital, which is assumed by
most cutting-technologies, is no longer related to some virtual dimensions
only, but emerges as a complex relation between the material and the
immaterial. Take, for example, the following process: a conceptual model is
quickly and manually made, photographed/3-D scanned, then entered into
the computer so as to constitute the basis of a digital model. The digital
model is then formed, and its 2-d geometries sent to a milling machine to
be cut. The cut parts are finally (manually) assembled using adhesives. Then a
mistake is discovered! Parts of the models have to be re-sent to the router,
others have to be re-edited, and so on. From the time of its inception as a
conceputal idea to its final form, the model has oscillated several times
between the electronic and the manual registers so much so that it is
almost impossible to find a unified definition of its ontological status at a
given point of its making.

This blurring echoes a line of thinking that goes back to the first
reflections on the interactions between analog and digital media which took
place a decade ago or so in several Acadia conferences, especially Acadia
1995 (Computing in Design: Enabling, Capturing and Sharing Ideas) and
Acadia 1998 (Digital Design Studios: Do Computers Make a Difference?).
These interactions included, for example, scanning a 3-D physical model for
developing elevations, or digitally extruding a scanned manual sketch done
from a video-taped “plan-view” of a 3-D physical model. As a result of these
natural or other more conscious experimentations, media interactions
allowed for new kinds of imagery and “representation fields” with a strong
hybrid, strange yet familiar “aura” conducive to metaphoric leaps assisting
the design and communication processes. The resulting novel depictions
began to suggest ways of architectural representation beyond the traditional
synchronous, unitary and Euclidean boundaries of orthographic or
perspectival constructs. Among the reported potential qualities are
representational shifting, simultaneity, multiplicity, temporality, speculation,
assemble, episodic fragmentation and typological hybridity. Likewise, the
unfolding between cutting-edge technologies and miniature tooling has
forced current model-making to reveal itself as a hybrid process involving
not only discontinuities or interruptions of the digital medium, but
complementarities and convergences between the digital and the not-so-
quite digital. The dependence on these interfacing events, that is on
diversified situations, techniques and technologies, is enhancing a new type of making that feeds on a technological migratory movement rather than technical exclusivity and uniqueness.

One specific entailment of this oscillation is the fact that model-making is becoming closer to the real act of building. If we assume that the building industry will soon take advantage of the extensive capabilities of CAD-CAM that have been exploited in the aeronautics/aerospace, automotive and shipbuilding industries, then it is easy to see the closeness between the current making of an architectural model and the construction of a building. We know that some firms in the shipbuilding industry have very large cutting tables and may well consider doing a little building-related activities on the side to keep their expensive equipment in constant use. Robot laser welders are also used in shipyards, where they can crawl about inside the double bottoms of ships, and could in principle be adapted to the architectural construction site. Many strategies being adopted by small boatyards are also highly applicable to buildings and range from specific layout and forming techniques for curved metal or composite shapes, though designing parts for self-alignment and embedded assembly information to development of customizable “product models” and re-engineering the entire process from design through commissioning to take the best advantage of available CAD/CAM capabilities [4]. The similarity of these applications in constructional and organizational complexity to that of buildings, as well as their tantalizing departure from conventional building forms, makes them natural extrapolations of the techniques used in the model-making lab.

This convergence could be seen at the level of the making process itself, as mentioned above, as well as the nature of materials used. Besides the specific nature of the cutting-edge/miniature tooling dialogue, one should point to the nature of materials used both in model-making and in the building industry. Modeling materials have their own physical characteristics, of course, which imply a reference to a wider realm of construction. They are chosen not only for the ease with which they may be handled, or for the usefulness they contribute to whatever visual service design requires, but also because they accommodate themselves to certain external empirical expectations. All the routines of cutting, attaching, positioning, templating, erecting and finishing that are present in a model-making session are pointers to similar and wider processes of building, like manufacturing, casting, erecting, attaching, cladding and polishing. The perceptual conditions established by the model are the very attributes, however moderated, of the future building. Take plexiglass for instance. It is fairly knowledge that the common features of this versatile material include lightness and the power to express both transparent and translucent surfaces. Because it can easily be cut, heated, twisted and glued, it constitutes an ideal medium to quickly express both simple and complex design ideas. Even without the immediate reference to a specific building material, it is obvious that it (plexiglass) can
establish an order within which there is a direct link between form and matter. And if the plexiglass sheet is not the real glazed façade of the future building, it certainly can constitute a very credible manifestation of a glazed appearance. It may not bear a convincing physical relation to glass, but it can echo the very experience of handling glazed components.

Of course, the above convergence of cutting technologies and miniature tooling at the model-making level may not be exactly mirrored on the real construction site. The problem of size and the typical nature of modeling and building, with all the empirical requirements embodied, dictate different modes of constructing 3-D forms. Suffice to argue, though, that more similarities between the two spheres will become evident in the future, including in terms of the convergence of automated technologies and less sophisticated tools. For in both model-making and building construction, the reliance on CAD/CAM techniques will always stipulate a more conventional component to fill the gaps that cannot be addressed by the laser cutter, the CNC router or the rapid prototyping device. The advanced model-making lab, in this sense, seems to be heading toward becoming the site where real building issues will be simulated and anticipated. A subject worth-following indeed.

6. CONCLUSION

Although the cutting-edge technology of CNC/Laser Cutting and Rapid Prototyping is an essential parameter in any serious effort to build models nowadays, the role of miniature tools and accessories is equally important. This new situation means that the status of the model is to be defined in terms of a convergence of particular technological possibilities, a fact tested through the making of a wide variety of models, two of which have been particularly debated in the present article. It has been stressed that this reality is now allowing a smooth and fluid dialogue between the two forms of model-making techniques, with some noticeable theoretical entailments. One specific entailment is the fact that model-making is getting closer to the real act of building. If we assume that the building industry will soon take advantage of the extensive capabilities of CAD-CAM that have been exploited in the aeronautics/aerospace, automotive and shipbuilding industries, then it is easy to see the closeness between the current making of an architectural model and the construction of a building.

This closeness could be witnessed in terms of the technologies, the process of making itself, and the nature and application of the materials used. Alongside these similarities, there is also a convergence of the manual and the digital aspects of the making process. The meeting of cutting technologies and miniature tooling at the model-making level may not be exactly mirrored on the real construction site. For the problem of size and the typical nature of modeling and building, with all the empirical requirements embodied, stipulate different modes of constructing 3-D
forms. Yet it is possible to argue that more similarities between the two spheres will become evident in the future. A new vocabulary of making could apply to both models and built structures as a consequence. The advanced model-making lab, in this sense, seems to be heading toward becoming the site where real building issues will be simulated and tested before their implementation on the site, a point that could be developed in future investigations.

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References


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