Form D-Form

A design studio on digital fabrication and thermoforming

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The paper discusses an experimental design and fabrication process which employs digital fabrication and thermoforming. It presents the outcomes of a postgraduate design studio which took place at the Department of Architecture of the Aristotle University of Thessaloniki in Greece. Although thermoforming is a well-known process for product and packaging design, it has not been extensively explored with regards to architectural applications. This research by design seeks to cast light on thermoforming combined with digital fabrication with the aim to devise new customized production strategies, that can afford the design and fabrication of unconventional geometric configurations.

Keywords: *Thermoforming, Digital fabrication, Form-Finding, Research by Design, Freeform architecture.*

INTRODUCTION

Although manufacturing processes of thermoforming are well known in the industry world and have been used extensively in product design and packaging, there have been very limited architectural applications. Considering the fabrication challenges of free-form architecture facades, various formative manufacturing processes seem to provide a feasible solution for double curved panels (Castañeda et al., 2015). The ever-growing need for customization in architectural design and construction (Naboni and Paoletti, 2014) requires us to revisit old tools, combine processes and methods and devise new design and construction strategies that will respond to multiple parameters, including geometric precision, cost, construction speed, among others. Researchers agree that thermoforming processes are becoming an "attractive fabrication technique for new and innovative lightweight structures" (Okuda, 2009). Among their advantages is the capability for rapid mass production of doubly curved surfaces. A thin plastic sheet can be easily heated and deformed, increasing its stiffness through geometry. One of the drawbacks of forming processes is the high cost of the initial mould, however digital fabrication technologies, laser cutters, CNC routers and robots, can reduce the cost and construction time of the mould substantially. This has been one of the author's motivations to combine digital fabrication with thermoforming.

THERMOFORMING MODUS OPERANDI

Plastic thermoforming is the generic term to describe the plastic manufacturing process that heats thermoplastic sheet material to a pliable temperature and then applies pressure or vacuum to form it into a tridimensional shape using a mould (Fig. 1). Following the formation process, the sheet is trimmed to a predetermined shape to create a finished product part. Pressure and Vacuum Forming are the two most common plastic thermoforming manufacturing techniques, the main difference is whether positive pressure is applied above the heated plastic to press it on the mould, or whether negative pressure between the mould and the heated plastic pulls it onto the mould. Thermoforming is a manufacturing process that is very common in product design and packaging (Klein, 2009). During thermoforming, the heated sheet acquires a temperature that permits it to be stretched into or onto a mould and when it is cooled it retains the shape. Thermoforming is normally an industrial manufacturing process, that uses wooden or aluminum moulds that can resist pressure without deformations, to produce thousands of parts to be used in industrial applications. The sheet material is fixed within a frame near its perimeter. When heated, either the frame is lowered so that the thermoplastic wraps around the mould, or the mould that is fixed on a movable bed moves vertically to reach the stretched thermoplastic. For concave moulds it is often important that there are some apertures in the mould, so that no air is blocked between the mould and the plastic sheet, the pressure or vacuum will ensure that the plastic sheet reaches all the cavities and adjusts as precise as possible to the geometric boundaries of the mould. The most common materials used are Acrylonitrile Butadiene Styrene (ABS), High-Impact Polystyrene (HIPS), High-Density Polyethylene (HDPE), Polyvinyl Chloride (PVC) and Polyethylene Terephthalate (PET).

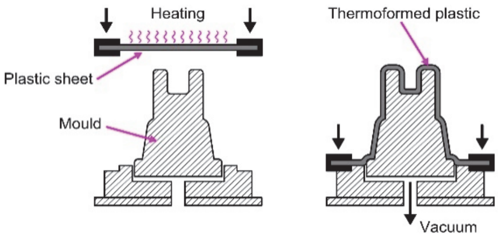


Figure 1
Basic thermoforming process

PRECEDENTS OF THERMOFORMING IN ARCHITECTURAL RESEARCH AND PRAXIS

There are relatively limited precedents of thermoforming in architecture, when compared to other manufacturing processes such as CNC milling and 3D printing. Prominent architects such as Peter Cook, Toyo Ito and Frank Gehry have employed thermoforming of glass panes or plastic tiles in their work, however always with a deterministic goal to create a one-to-one replica of the mould and seldom with the research aim to explore emergent material properties and formations. Award winning Variable Vacuum Forming Wall (VarVac) by HouMinn Practice with Philip Bussey employed a low-cost strategy to create an acoustic wall for University of Minnesota School of Architecture (Swackhamer and Satterfield, 2013). Kine-Mould produced as a joint project between TU Delft and TU Eindhoven is a development for forming thermoplastic polymers as well as concrete elements (Schipper et al., 2014). AIA pavilion was fabricated from thermoformed plastic sheets. As Gernot Riether (2011) explains, for the pavilion three thermoforming techniques were investigated; draping, drape-forming, and vacuum forming, and a flexible mould was developed that could adapt to different triangular geometries.

Moulds of double curvature can also be created by a grid of numerically controlled pins of adjustable height, which may be used either for glass, plastic sheets or metal. The logic of forming is similar, as all three materials become malleable within certain temperature range. FlexiTool is a pin system that was used to form PMMA panels for renown Graz Kunsthaus (Alonso et al., 2013). A similar pin system for metal sheets, the multipoint stretch forming, was developed and used for the Dongdaemun Design Park (DDP) building by Zaha Hadid, employing a hybrid method of multipoint forming and stretch bending (Castañeda et al., 2015). The IsoMachine, a rod system developed at the University of Innsbruck, can form heated polystyrene boards on a doubly curved surface mould that comprises of 400 rods that are robotically placed and locked in place. The outline of the polystyrene boards is preserved with the help of laser-cut wooden frames (Fereos and Tsiliakos, 2014).

Kieferle and Katodrytis (2016) envision alternative moulds for vacuum forming by using sand which is shaped manually or machined by CNC routers and robots. Loh and Leggett (2017) explore the potential of a ReConfigurable Edge Mould (REM) to produce variable shaped panels through thermoforming. This configuration investigated the fabrication of minimal surfaces by constraining the heated plastic within a fixed external boundary and a “shaping object” that would act as an internal boundary to stretch the malleable material until all forces reach equilibrium, creating the characteristic geometry of minimal surfaces. Weissenböck (2014, 2015) employs a similar procedure for robotic thermoforming, she develops a special kind of "dynamic mould" to form flat acrylic sheets which are heated and robotically pushed against a form-giving counterpart: the "deformer tool". The robot's movement together with the deformer tool act as a dynamic mould, capable of implementing complex movements like push, twist and tilt.

FORM D-FORM DESIGN STUDIO

With the aim to further explore the potential and limitations of thermoforming in architecture, Form D-Form, a postgraduate design and fabrication studio was set to explore digital fabrication and thermoforming, the correlations between the two processes, the morphogenetic strategies, the seamless design-to-fabrication data transfer, the material feedback and design modifications. During the studio, students explored different digitally fabricated mould configurations. Among the interesting findings was the material behaviour as well as the unpredictable emergent forms of the prototypes, a negotiation of form, forces, temperature and materiality. It was interesting to experiment with discontinuous moulds, to explore the geometric outcome of thermoforming in supported areas as opposed to the unsupported regions where the thermoplastic material would shag, and the final form would be the result of negative pressure and surface tension of the heated plastic, leading to formal configurations similar to minimal surfaces (Fig.3). The aim was to combine digital fabrication and thermoforming to devise a design strategy that explores the creative potential and also the unpredictable emergent formations of the material for given boundary conditions. The intention was not to create an exact replicate of a mould, but to discover spatial qualities and textures that may emerge from variable densities of the support structure and the geometry of the mould. Similar to the form-finding of membranes and inflatables, thermoforming is a dynamic process; the material (in its heated condition) self-organizes to obtain a stable form supported by the formwork and maintains this form after it cools off.

The material behaviour in this experimental set up feeds back into the design process, to adjust design decisions such as the density or the height of the underlying beams. Based on the findings from test models, the students were able to digitally simulate the material behaviour by tweaking different parameters of mesh stiffness and subdivisions and adjusting the formwork accordingly. Students were encouraged to engage in hands-on exploratory design activities, that combine digital and analogue tools, materials and processes and discuss the advantages and drawbacks of this novel design-fabrication method.

The studio’s experimental infrastructure included a range of hardware and software tools and materials. The machinery included two large scale laser cutters, a 3 axis CNC Router and a Vacuum Forming machine (Fig. 2). The software tools employed were Rhino3D and Grasshopper, together with additional plugins for physics simulation (Kangaroo) and mesh editing (Weaverbird). The materials used were PVC sheets for the thermoforming and timber, MDF, cardboard and polystyrene for the mould.

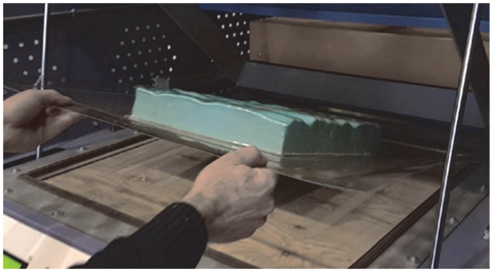


Figure 2
Thermoforming of a PVC sheet on a CNC milled polystyrene board to create a rippled surface panel

Preliminary experiments and methods

As thermoforming was a relatively new process for architecture students, it was crucial to understand the modus operandi of thermoforming, the benefits and limitations, and inform the design strategy accordingly. Following a series of preliminary prototypes, the students came up with a series of empirical observations that relate to the material and the machinery settings.

- The **thickness** of material is of crucial importance. Below certain thickness the material may fail in two ways, on one hand it may snap out of the frame, on the other hand thin material is prone to tearing when stretched. Above certain thickness the material will not wrap around the object enough to acquire the desired geometry.
- The **temperature** should also remain within certain range. A cold temperature would result in a coarse representation of the underlying geometry, while a very warm temperature would reveal more details than required, accentuating material discontinuities or defects of the underlying structure.
- The **changes in height** of the underlying mould geometry should remain within certain range, so that the thermoplastic material doesn't break. A very high protrusion in z axis may force the material to stretch too much, decreasing its thickness locally, resulting to ruptures due to tension.
- The **sharpness** of corners may also affect the performance of thermoforming, as sharp corners can easily tear the material apart therefore terminating the suction process due to negative pressure.
- The **apertures or discontinuities** in the mould are decisive. Apertures are necessary for eliminating the air between the thermoplastic and the mould, however a small hole will not be visible on the plastic outcome, while a bigger aperture can cause material to shag or form minimal surfaces (Fig.3).
- The mould or formwork should display **structural stability** under stress. The forces exerted on it during the thermoforming process may move its elements or even destroy it, jeopardizing the outcome of the prototype

The above observations are rather qualitative and cannot be quantified easily. Nevertheless, they may act as generic guidelines for design decisions; often there are more than one of the above parameters in play, in occasions these parameters can act synergistically and bring a positive design outcome or accelerate failure due to material tearing.

Studio projects exemplifying limitations and opportunities

Following the initial experimentation phase, the students in teams of three developed their design ideas, through algorithms and prototypes. Four of these projects are presented here.

Figure 3
Formwork made of cardboard tubes of parametrically defined variable height

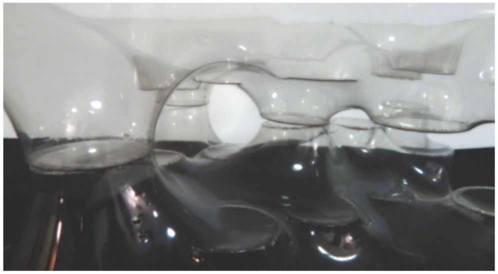


Figure 4
Thermoformed prototype exhibiting areas of minimal surfaces

Project 1 employed cylindrical tubes of thick cardboard, assembled together in different heights based on attractor points. The amount of the cardboard tubes as well as their heights and distances were controlled through a Grasshopper definition. The thick cardboard was resistant to the applied pressure, however in some experiment iterations, the cardboard tubes would fall or destabilize during the forming process. After several tests and by assessing the model failures, it was decided to fix the carboard tubes on a base, made of extruded polystyrene (Fig.3). Several iterations of thermoforming were necessary to fine tune parameters of heat, time, suction. The thermoformed prototype displays geometries that resemble minimal surfaces (Fig.4). The results of the preliminary tests informed the design parameters.

Project 2 comprised of smaller components that were formed over polystyrene and were later assembled together to form a larger element (Fig.5). The underlying computational logic related to the curvature of a reference surface, which was divided in smaller isosurfaces. Based on the colour mapping of the curvature of each isosurface, 6 groups of surfaces were created. Each group of surfaces was to be reconstructed with pyramidal spikes of differentiated height (Fig. 6). Although the initial idea was the creation of sharp spikes, the heat and pressure of the thermoforming process, converted the sharp corners of the pyramids into rounded peaks (Fig. 7). This was a rather unpredictable result but after the initial tests, it informed the digital model and was incorporated in the design, providing the overall shape with an organic texture.

Project 3 was inspired by erosion patterns and structures found in nature. The design is algorithmically defined (Fig.9), employing marching cube algorithms and dynamic mesh smoothing (Piker, 2013). The project's design contains a great amount of cavities and the initial thermoforming tests failed to create an accurate geometry of the erosion patterns. Subsequent tests with the insertion of holes in the mould aided the vacuum function substantially, therefore increasing the definition of the geometry (Fig. 8).

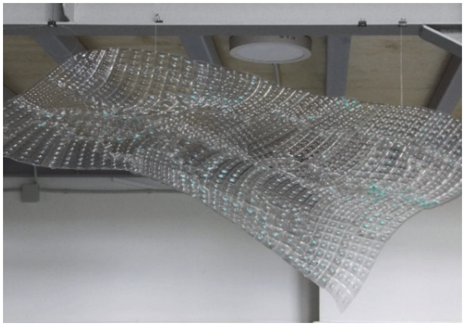


Figure 5
The final assembly of the "Crocodile Skin" surface consisting of 35 thermoformed elements

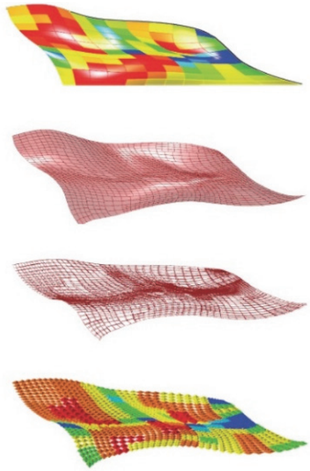


Figure 6
(a) Curvature analysis of the base surface
(b) Variable subdivision of areas
(c) Box height based on colour
(d) Morphed geometry on the initially referenced surface

Figure 7
Thermoforming converted the sharp corners of the pyramids into rounded peaks

Figure 8
Thermoformed tiles exhibiting relatively high geometric precision after the addition of holes in concave areas

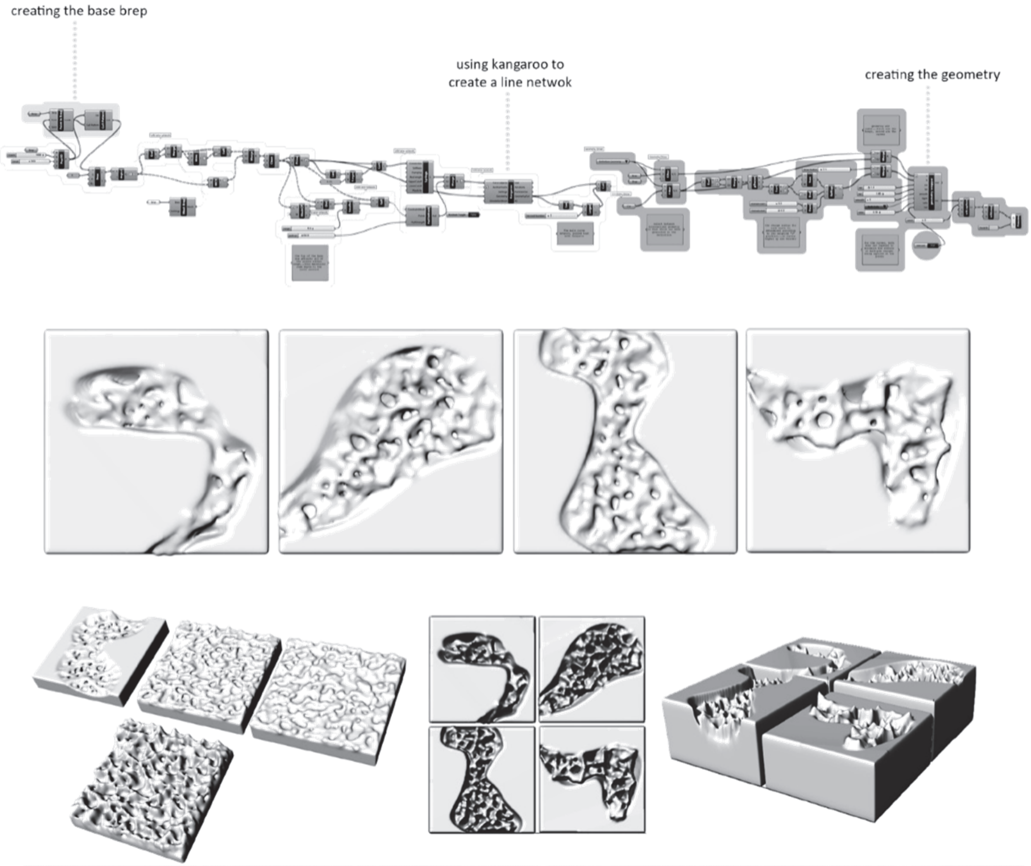
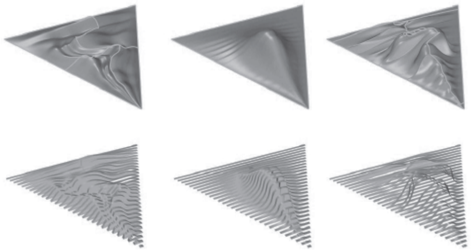


Figure 9
Algorithmic definition of tiling patterns to be used for thermoforming

Figure 10
Algorithmic experiments for the sectioning pattern of the pyramids



Project 4 was composed of pyramids that were created with 3mm MDF sheets. The pyramids were parametrically defined, and several sectioning patterns were tested (Fig.10). The triangular parts were laser cut and mounted to create each pyramid. It was seen that, as opposed to polystyrene models, the gaps between the sections enabled the air to flow freely, thus facilitating vacuum between the heated PVC sheet and the pyramidal mould, leading to models that were more accurately following the geometry of the mould. The pyramidal MDF construction was structurally stable as it was arranged with beams in both directions. Therefore, the mould could be easily reused to create more pyramidal shapes that were later assembled into a bigger structure (Fig. 11).

CONCLUSIONS

The aim of the workshop was to explore new possibilities of thermoforming for architecture and design and understand how the actual material feedback can inform the digital design process. Initial experiments aimed to decipher the optimal conditions as well as the constraints of this fabrication method, the material behaviour for different temperatures and variable mould geometry. Due to the material and machinery limitations and the actual nature of thermoforming, students created processes capable of adapting to unexpected results and tried to incorporate the problems that emerged as a creative hint towards the next step. By closely examining the objects created in the studio, it was seen that thermoforming renders much more accurately the subtler variations of a surface, as in the experiments of rippled surfaces (Fig. 2) than the ones containing spikes and sharp corners (Fig. 6 and Fig. 11).

Figure 11
The final assembly of thermoformed pyramids

It was often observed that air got trapped between adjacent peaks, and the PVC sheet would never come to enfold them completely. Instead, it would create a fold of material between them, a physical blend. By introducing holes in the mould at concave areas, or in areas of greater height variation, the air can pass through, and the vacuum force is accelerated, leading to higher geometric accuracy. Parametrizing the density and size of the holes proved to be useful, smaller holes would not affect the suction effect significantly, while bigger holes would be visible on the thermoplastic, leading to the decision to insert smaller holes at higher densities near the problematic areas. This observation was fed into the Grasshopper algorithm, to automatically generate holes in the mould when necessary.

The studio's objective was to combine processes of digital fabrication and thermoforming in an ad hoc fashion, observing the specificities of the material and machinery, fine tuning the process through empirical response to the material behaviour and using this input to modify the design algorithm accordingly. The capacity of thermoforming to erase the geometric details of the mould or to accentuate them on demand is a very interesting feature, as it gives the designer the choice to either smoothen or sharpen the geometric definition based on the design intent. Future research should implement the learnings from thermoplastics and opt for more sustainable approaches, with reusable moulds, biobased materials and environmentally conscious processes.

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