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Encrusted and Patterned 3D Manufactured Hybrid Materials for Architectural Application

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***Abstract* – Article focuses on the workflows for generating new hybrid material explorations for architectural application through development of new strategies of applying parametricism as one of the main driving forces in the design that exercises novelty through 3D modeling and visual programming languages. The obtained results have been applied in series of material design experimental sample projects that challenge the standard geometries and enhance the field of applicative materials for architectural application.**

***Keywords* – 3D manufacturing, encrusting, hybrid materials, innovative interiors, seamless patterns.**

Introduction

The setup of this research is based on an ongoing research to develop new strategies and procedures for treating classical materials like wood, metal and stone with the help of the new technologies to be used in architectural application. These technologies are CAD / CAM based procedures applied in a series of operations for new repetitive and / or unique patterns that are in constant development to create avant-garde ways of mixing the different techniques and reaching new visual and esthetic qualities. Most of the materials have been treated with two-dimensional engravings and / or 3D milling procedures, or combinations of the both to cast negative molds and afterwards fill them with liquid state original materials like different concretes and resins. The final step is to mix and match the best possible new combinations of the previously described pieces into compositions that are infinitely looking for non-standard usage scenarios in interior or exterior architecture, while elaborating signature portfolios of material samples.

I. State of the Art in Architectural Materials and Geometries

Architectural materials have developed in human era from all-natural direct usage of raw untreated forms and simple elementary shapes to technically advanced manufactured artistic expressions. In contemporary architecture most of the materials are being used in their natural composition, in most often standardized sizes or custom made to fit specific dimensions. Significant part of the materials are treated and industrially manufactured and we always see fewer materials in their natural untreated form, for example, entire wooden slab used as massive wooden countertop or any other piece of decorative surface. Often materials are additionally treated to add color, tint or additional features like roughness, shine and other special textured effects. Specific group of materials are tiled to standardized square, rhomb or semi circular geometries, like ceramic tiles and natural or man-made stone pavements. The same applies to systems of façade panels and most of the interior paneled surfaces.

Last two decades with the advance of Computer Numeric Control (CNC) fabrication becoming more affordable, we would expect to see the shift from mass-production to mass-individualization. This should be possible as the manufacturing processes have become fully computerized so the design variations should be achieved by changing the numeric control files that run the CNC machinery. In theory that would also foster the possibility to adapt full zero-waste principle, when the materials would be made on demand, and in such geometries that create the original design without any leftovers. But in practice this is not happening due to a combination of various aspects like economical feasibility of everything already standardized, lack of education and relatively low demand of unique designs, related to cost of individualized fabrication and design labor. It is also very stereotypical that the orthogonal designs sell better and in far bigger quantities than non-standard designs. Such design is easier to stack, store, transport and even install, as everything is readily available out of the box in default sizes. Architects work with designer series materials that are catalogued, so it is more a process of mix and match rather than creation of something new in its artistic sense.

In order to produce original designs, it is possible to draw parallels with advanced art or get inspired from nature. For example, the geometrical patterns are typically present in a texturized way either as simple and repeated lines, circles, squares or their reconfigurations much more rarely than organic shapes and forms. Art always follows the latest novelties and goes ahead of achievements in architecture, but it does not implement into the demand as fast as traditional or so-called "proven" classical designs. Recently the work of architects that has been digitalized by such social mobile device application as "Pinterest", serve well for inspiration, but it does not promote a regular non-designer person to dare to ask for anything innovative, rather refer to already existing designs and reconfirming them to be applied in his own project. So old designs get reused again and again, leaving less space for new.

To see further possible complexity that is in the other extreme of everything rectangular and regular but still repeatedly patterned, we may refer to a notable advanced thinker of the last century, Dutch graphic artist M. C. Escher, who has made great artistic contribution by using such elements as duality of color, mathematical symmetries and variably changing (parametric) tiling tessellations, all worth researching to see transitional

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patterning of seemingly standard geometries from another, almost surrealistic perspective. The concept of duality is the central concept in the work of M. C. Escher [1], where the opposing ideas, their states and perceptions, as well as the complementary form or juxtaposition of an object and its background can be perceived only one at a time (see Fig. 1). This creates a very dynamic visual image that is either black or white, where the borders of one object define the second inverted image, and vice-versa.

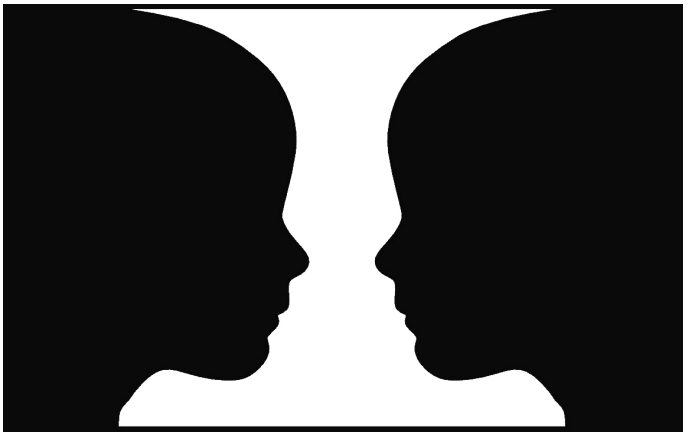

Fig. 1. Two opposing faces or a vase? A typical dichotomy researched by psychologists [Figure: A.Riekstiņš].

In architectural materials opposing colors are also being used in a tiling that often is referred to chessboard or taxi-sign layout. Most of visually appealing periodically repeating designs are usually black and white, and the reasons for using these color combinations are contrast, bringing out certain detail, balance, and symmetry. Historically this method has been so much used since prehistoric art that there is a need to develop new ways of patterning while using the congruent dark and light materials next to each other.

II. Material Experimentation in Academia

All schools of architecture usually teach a course of materials for architects, and very often it is complemented with working with some of the materials and making small samples. This research was set up with a special attention to new digital workflow methods at an academic environment with three small groups of the fourth year students of architecture of the University of Monterrey, Mexico, in a semester-long elective study course "Materials and Finishes for Interiors", fostering the implementation of advanced fabrication into traditional finishing materials for architecture. The course was taught in three consecutive 16- week semesters from August 2017 to December 2018.

The practical part of the curriculum was divided into three stages.

- Exploration of two-dimensional repetitive patterns based on Cellular Automata or on the rules of The Game of Life, and creating the first non-standard tiling concepts, inspired by pure geometry and graphical artist M. C. Escher.
- 3D modeling and parametric design application for volumetric patterns, CAD / CAM fabrication of prototypes from classical architectural materials – milling of woods, laser engraving of metals and stone, casting concrete tiles, etc.
- Elaboration of advanced digital signature and shape grammar for hybrid composites with casting resin to digitally originated molds and mixing techniques of encrusting and patterning materials with as much of technology application as possible. The final work included also a creation of physical portfolio sample enclosures with thermoforming equipment.

Besides all of the practical work on experimentation, students were given a profound know-how of materials and their qualities from the usage of stone since the prehistoric times of 300 000 or more years ago [2] to recently developed contemporary composites. A series of detailed lectures was included about different classes of architectural materials, which continued throughout the semester in a more specific material and fabrication focused attention while applying the theory in practical exercises. One of the great sources to be inspired from and referred to by the multitude of possibilities within the professional field was the introduction of *Material ConneXion* materials library – a cutting-edge collection with hundreds of physical contemporary material samples, which is available in the Garza Sada Centre (CRGS) building in the University of Monterrey campus.

During the steps of the practical curriculum, every student worked with geometrical grammar of his choice, developing complexity and piece by piece elaborating his full final portfolio collection. In depth this is explained in the following three subchapters, given five weeks of studies for the elaboration to each of them.

A. Tessellation Tiling

The first step was learning parametric design principles using Rhino plug-in Grasshopper and exploring the changing of resulting patterns while playing with different dimension input values. The strong advantage here is that most of the modeling for CAD / CAM application in academia is being done with Rhino anyway, so learning new functions did encourage the design quality. The design involved creation of symmetrical compositions that could repeat on a square, rectangular, triangular or hexagonal grids, always fine-tuning the dimensions and their internal relation parameters. Symmetries are the most elementary of all space relations [3], a stable starting point for a tessellation exercise. If one edge of four-sided geometry is modified and copied to the opposite edge, this piece like a puzzle piece will still stack together perfectly. This can be applied also in a regular rotation, as long as it stays in the equal range of 360 degrees circular division and rotation (see Fig. 2).

Once the main shape was obtained, most of the students mastered it to the maximum geometrical complexity that can have many different states of composition, basically tiling in multiple

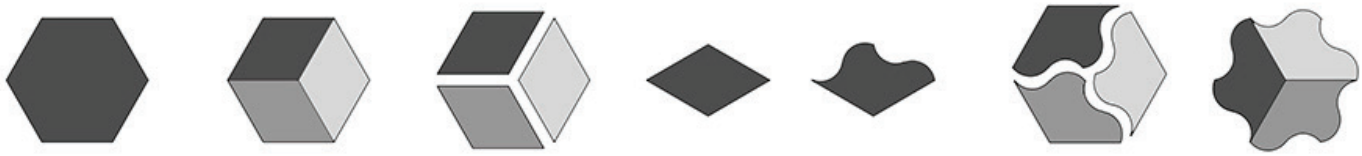

Fig. 2. Series of a hexagonal division into three four-sided rhombs that rotate around 120 degrees, further one side is being transformed into a wavy curve that stacks the matching inside and / or outside edges together into one uniform piece. Author: Fernando Hinojosa, class of Autumn 2018 [Figure: F. Hinojosa].

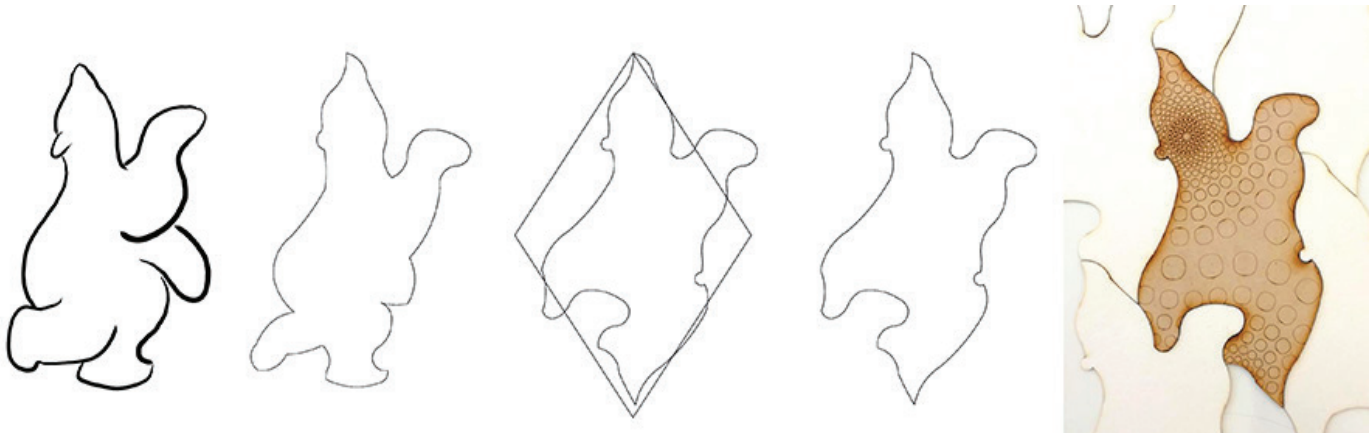

Fig. 3. The evolution of "B Tile" from initial sketch through a tessellation of a four-sided rhomb that copies the opposing edges to master the perfect geometric duality and visually perceiving the bear contour as a one uniform shape. In the final stage, a parametric pattern is applied as a two-dimensional graphical feature. Author: Barbara Castellanos, class of Autumn 2018 [Figure: B. Castellanos].

possible arrangements, while some students worked on a more straightforward graphical proposal, like "B Tile" that resembles an image of a dancing bear (see Fig. 3).

Next arises another issue related with the edge tolerances, as the repeating regular patterns have equal space between the repeating pieces while irregular designs because of the deformed curvature cannot have such gaps, and usually feature a different width of gaps around the edges (see Fig. 4). To eliminate this problem, all of the further designs had no gaps, e.g. they were seamless designs with a future option to do inward-oriented offset from each piece's contour to generate, if necessary, regular spaces between the neighboring elements for easier material installation.

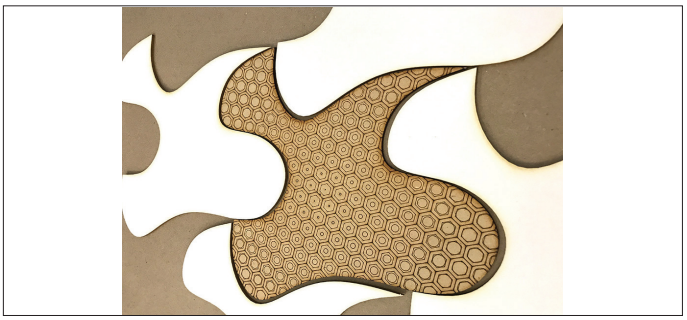

Fig. 4. Perfectly tessellated object of approximate 200 mm width set apart with a 5 mm distance in x-axis results in a very irregular gap separation along the curvy edges, at places being variably apart from each other while at places totally touching. Author: Paulina Escamez, class of Autumn 2017 [Figure: A.Riekstiņš].

Each student also developed a unique experimental parametrically changing pattern to be applied as a two-dimensional engraving imprint that further in the next two course stages would be developed into full 3D shape manipulations in the z-axis depth of the elements. The design was more graphical, looking for a visual quality in order to complement the shape of each element. In this stage, the work was fabricated with laser cutting and engraving one patterned element in 3 or 5 mm thick MDF and additional six to eight matching pieces of the element contours were laser cut in white thick cardboard, to showcase the continuity seamlessness of elements.

Now, if these tiles would need to be arranged in a larger composition being made of dark and light pieces, in a standard situation this color combination could be arranged in a chessboard layout. But researching the field of simple generative patterning we can reference Cellular Automata (CA) – a model of simple organism in computer science, mathematics, physics, complexity science, theoretical biology and microstructure modeling [4]. CA principle gives us more bottom-up strategies to choose from alternative dual color patterns to be applied in a larger composition. The CA is made of cells that can have two states – black when they are alive or white when they are not. Stephen Wolfram, who has systematically studied CA, discusses the simple programs to be a scientific discipline of its own, argumenting that it is also the minimal possible form of science, grounded in abstraction and empirical experimentation [5]. The "life" itself is programmed as

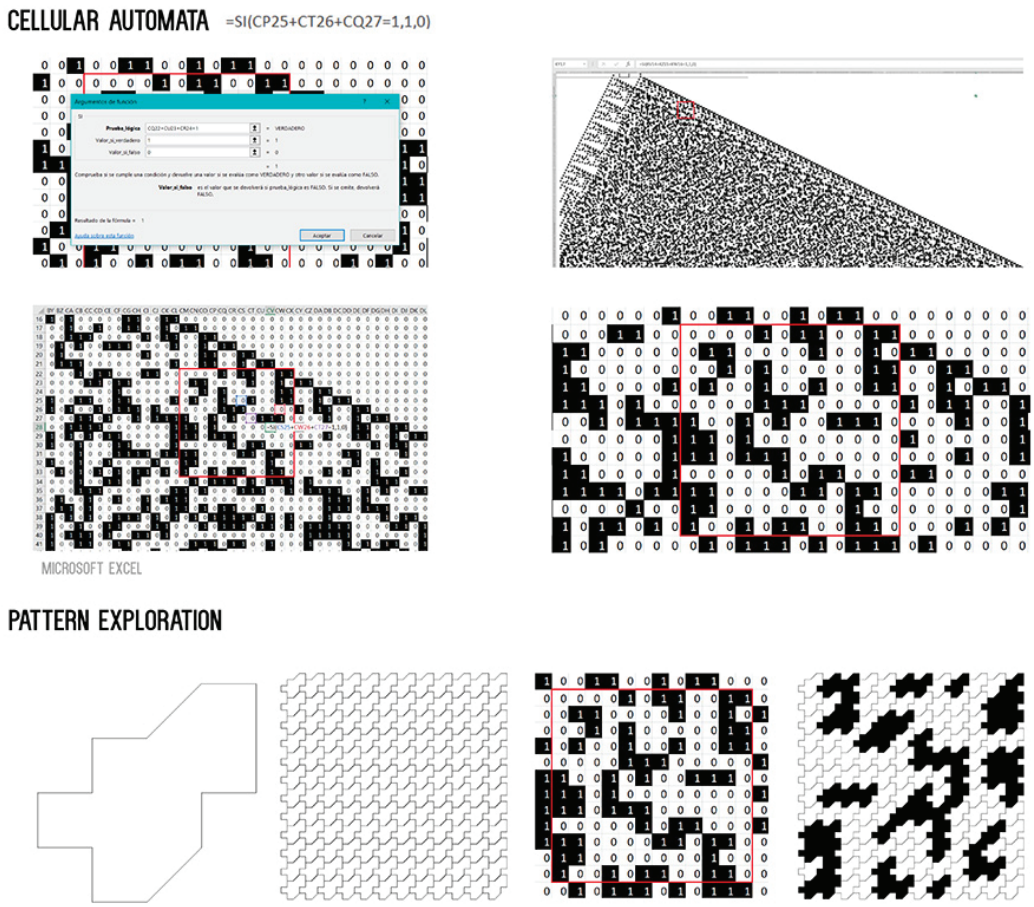

Fig. 5. Programming Cellular Automata in Excel with an "IF" formula and conditional formatting to color the resulting cells either black or white. Afterwards the desirable fragment is being chosen and applied to a matrix of individually designed tiling panels. Author: Valerie Sánchez, class of Spring 2018 [Figure: V. Sánchez].

a state of the next cell in relation to the previous cell, defining a formula that calculates the result. Due to the simplicity this could be very well obtained in any spreadsheet program like Microsoft Excel that was used for this particular application. Ending this design step authors translated the alternative CA-originated patterns to their compositional arrangements (see Fig. 5).

B. Advanced Material Samples of CAD / CAM Prototypes

In this stage the previously developed pattern was applied in full 3D, proliferating the individualized parametric patterns in z-axis depth via series of Boolean operations. The practical work involved usage of different modeling strategies and also advanced programming for manufacturing, as the materials in this stage were all about classic values in new expression – mainly wood, metal and concrete, processed digitally (see Figs. 6 and 7).

For wooden materials students worked with regular plywood, Chilean pine and hardwood Banak (in Latin – Virola) with a thickness from around 3 / 4 inch (19.05 mm) to 1 inch (25.4 mm). The fabrication was done on a 5-axis CNC milling machinery to extract the excess material via routing with a drill bit of 6.35 mm and for the finest details using a drill bit as small as 1.5 mm. For the stone materials different varieties of local Mexican and imported marbles and granites were water-jet cut and further laser engraved. Sheet metal was also cut with water-jet machinery, but the pattern here was taped on top with digitally cut vinyl decal and treated with strong ant-acid to start the oxidation process and therefore create a rusted pattern. Concrete pieces needed a negative mold to be made in dense extruded polystyrene, also with CNC machinery. The mixes of concretes were all gray with regular Portland cement and grey sand aggregate or all white made with white *Cemex* branded cement and fine marble sand with coarse marble gravel of 5–6 mm aggregate.

After reviewing the samples from this stage after 6 and 12 months, the acid treated sheet metal pieces had acquired more patina as they had continued the corrode and now were covering the entire piece with rust. The tonality of the corrosion was varying and ranging from dark brown to bright orange, depending on whether the part was originally exposed to direct acid or not (see Fig. 8). The fact of developing a new texture that involves the time factor adds new artistic and esthetical quality to the original work, underlining that the process to achieve the final look may often be time-consuming and laborious.

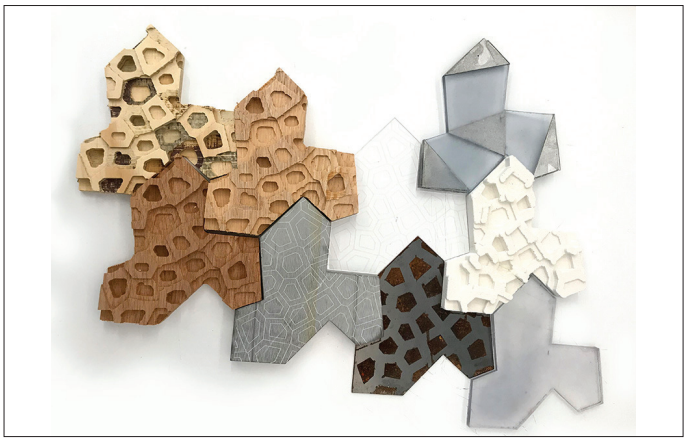

Fig. 6. CNC milled samples of plywood, pine and hardwood, water-jet cut marble slab with laser engraving, laser cut acrylic glass with laser engraving, sheet metal treated with acid through vinyl, white concrete cast in a CNC milled negative extruded polystyrene mold, and resin cast in a rubber mold. The concept of geometries is repeating displacement tessellation along hexagonal grid. Author: Ana Lucía Estrada Castillo, class of Spring 2018 [Figure: A.Riekstiņš].

Fig. 7. More CNC milled samples in curvilinear shapes with a repetition along 60 degrees or repetition in sideways 180-degree rotation for a more complex composition of mosaic. Author: Sara Gabriela Méndez, class of Spring 2018 [Figure: A.Riekstiņš].

Fig. 8. A sample of acid treated sheet metal. The pattern is undergoing a continuous process of corrosion. Author: Andrea Vidal Barroso, class of Spring 2018 [Figure: A.Riekstiņš].

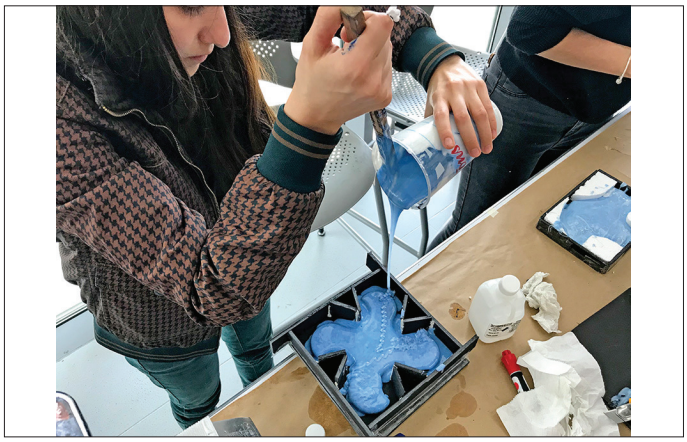

Fig. 9. Mold making with liquid silicone rubber in a foam board box over a solid MDF laser-cut piece. Author: Priscila Ramírez de los Santos, class of Spring 2018 [Figure: A.Riekstiņš].

C. Encrusted Hybrid Composites

The repeating patterns are far undervalued as artist M. C. Escher himself developed a series of patterns that are realized for example in the Poincaré disk model of hyperbolic geometries [6], meaning that there is a lot of potential for developing more advanced tessellations if the possibilities of geometry are being explored, the only limit being one's creativity. Therefore the third and last phase of work involved developing encrusted hybrid composites – materials that recombine into new non-standard assemblies to emphasize the geometric potential with new material usage strategies. Very often the economical factor of individualized design is seen as the biggest drawback for execution of a project. To cast a unique shape in a liquid carrier material, we need a mold. Often the cost of the mold actually exceeds the cost of the panel itself. Thus there is a strong incentive to reuse the same mold for the production of multiple panels to reduce the overall cost [7]. The idea to create multiple versions of the same mold takes us one step closer to zero-waste principle, as the hybrid samples can be obtained using the volume of the original material only in the necessary amount, making as many elements as needed and completely without waste. From the point of view of sustainability this should help in the strict requirements to certify an architectural object to comply with LEED (Leadership in Energy & Environmental Design) or NZEB (Net Zero Energy Building) standards.

In this stage, the first step was making a unique negative mold out of liquid silicone rubber that was thickened via catalyzing it during the cast over the duplicable original piece (see Fig. 9).

Further students learned to cast clear resin pieces, then to work with pigments and various basic inlays to achieve more decorative

Fig. 10. Filling pinewood element perforations with different intensities of the color pigment and achieving a gradual transition of the shade. Author: Valerie Sánchez, class of Spring 2018 [Figure: A.Riekstiņš].

Fig. 11. Plywood milled in variable depth revealing its various dually dark and light layers of pine, filled with resin that is all in one uniform light blue color, but due to the different depth it has the quality of water that absorbs and scatters the white light. Author: Néstor Isaías Torres García, class of Spring 2018 [Figure: A.Riekstiņš].

Fig. 12. Total mix of all digital and manual cast techniques, learned in the study course "Materials and Finishes for Interiors", showcased in a styrene thermoformed case. Hybridized materials (from top to bottom): resin cast concrete with gold acrylic paint, translucent red resin with Chinese paper, MDF cut flower design with dual color black and transparent resins, water-jet marble slab, sheet metal treated with acid through digital patterned vinyl. Author: Rossana Garza, class of Autumn 2018 [Figure: A.Riekstiņš].

qualities. Often very simple artifacts like coal, pieces of steel chips, sawdust, etc. were encrusted into tinted resin. Some wooden CNC pieces fabricated in previous stage were updated by filling the milled cavities with pigmented resin. This created additional interesting effects, as some authors mixed the intensities of pigment (see Fig. 10) while others worked with one tinted resin shade that brought out the color change where the elements were milled deeper, like the water in the ocean that seems darker in deeper spots (see Fig. 11).

Finally everyone was developing their individual projects where the carrier material was by default resin with embedded total mix of random other materials that were experimented throughout the semester in new non-standard assemblies. Some authors mixed and matched very combined techniques where parts of the final elements were actual fragments of reused other previous material samples, while fused together with materials like concrete and additional digitally produced fragments (see Fig. 12). Many of the final composition proposals were organized in manually made thermoformed cases to showcase the best combinations of hybrid materials discovered in the course.

III. Discussion of Results

According to Rudi Vervoort [8]: "The Art Nouveau constitutes a watershed in the history of European art. Breaking away from the architectural vocabulary of the 19th century, it reflected both a fascination with nature, our source of life, and a faith in the future, in science and technology. Whilst it celebrated the former, the movement owed its existence to the materials that could now be mass-produced through industrial processes sup-

ported by technical innovation. This duality is one of the Art Nouveau inherent characteristics." This research project is being dual as well, because the student works that have been created in the experimental setup reveal a new insight into articulated complexity of possibilities within creation of new hybrid materials. It mixes technology with matter, studies of new shapes and forms. The combinations of digitally derived families of tiles have a potential to be worked into architectural projects of all scales. This creative and non-linear workflow brings out possible new aesthetic qualities while still being relevant to the possibilities of free form geometries.

IV. Conclusions and Future Work

Finishing the work author concludes the following.

1. The case studies of mixing materials create a new agenda and synopsis for innovative application of the results in architectural designs, both interior and exterior.
2. The workflow processes developed in the academic environment have a strong influence in increasing the design quality for future professionals.
3. Individualized fabrication leads to zero waste manufacturing.
4. Hybridization opens up fields of interdisciplinary know-how for architects to shift from mass production to mass customization.

As this is an ongoing author's project of experimenting in academia, the future work is to continue developing the contents of the course "Materials and Finishes for Interiors" while also applying the accumulated skills in a real applied project of creating an architectural design. The plan for 2019 is to work on developing a new line of design and creating composites with embedded electronics, for example, a concrete mosaic tessellated floor with encrusted LED lights into resin inlets, and wooden paneling system for interior and / or exterior application with added material performance and visual qualities.

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