TEAM-WORKING AND REVERSE ENGINEERING

Teaching Methods for Complex Architecture

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Abstract. This paper contains research and details of a work in progress on the implementation of advanced 3D precision modelling in an undergraduate curriculum. Core to the investigation is the undergraduate course Digitally Enhanced Construction and Fabrication (D.E.C.A.F.) at the Department of Architecture, California State Polytechnic University Pomona. The course tests the application of Reverse Engineering (RE) in a team configuration, Hot-Swapping (HS), and precision modelling of complex geometries with minimal programming/scripting input, taking in consideration the limited resources common to small-scale architectural practices. Reverse Engineering particularly enables students to extract information building assembly and executed details with precision, based on existing documentation. It is conducted in teams not only to emphasize and investigate efficiency of protocols but also to observe problems in developing threads in digital modelling. Hot-Swapping identifies the principle of replacing components of a building during active design processes without altering its general appearance. As a teaching methodology, it allows the investigation of required modelling accuracy, creation of prototypes and various versions of assembly alternatives. The current paper focuses mainly on 1) engaged procedures in Reverse Engineering, 2) the educational aspects of such an approach, and 3) the advantages and disadvantages of conventional tools in a collaborative modelling exercise.

1. Introduction

The course Digitally Enhanced Construction and Fabrication (D.E.C.A.F.) is a ten-week fourth year undergraduate elective course attempting to establish several criteria for the topic of new methods in architectural Computer-

Integrated Manufacturing (CIM) and fabrication. It touches subjects of team-working in digital environments, Reverse Engineering (RE), precision modeling, scripting basics, Rapid Prototyping (RP), new principles in architectural detailing, File-to-Factory principles and Hot-Swapping (HS) in architectural design processes. Throughout the presentation of these topics, students gather experience through team-assignments and hands-on, practical examples. This paper specifically summarizes these assignments and elaborates the academic value of RE in a class-room setting.

2. Tools and Course Configuration

For practical purposes, software can be ordered hierarchically into five categories (Schodek, Bechthold, Griggs, Kao, Steinberg, 2005): 1) Concept Modelers and Rendering Programs, including Rhinoceros, Form-Z, 3D Studio Max and Autodesk Maya; 2) Animation software consists of programs mainly used for walk-through or other simulations. The future potential for practical use in the building industries may increase through eventual integrated use of environmental optimization software such as Ecotect and others. 3) Entity-based Drafting Programs, represent the commonly understood range of CAD applications used for general purpose of 2D drafting such as AutoCAD and VectorWorks; 4) Component-based Programs, such as Autodesk Revit, Microstation and ArchiCAD takes extensive use of smart 3D-objects, so-called components which are essential criteria for BIM applications. On top of the list are 5) Design Development Programs, such as Catia/Digital Projects, SolidWorks and Pro/ENGINEER. These programs focus on solution-finding and resolving architecture on an aesthetic and technical level.

In general, the modeling process follows traditional assembly methods in a bottom-up technique. Design Development Environments differ drastically from this approach since their structure is Feature-Based and includes inherited object histories through transactions. Each component, based on a source object maintains an interactive relationship with its environment, which again is parameter based. Such relationship allows virtually complete fluid control and ability to automate changes in design in a complex 3D model, but also requires discipline in modeling and a thorough and competent geometric setup. Due to this difference in method such modelers have currently significant disadvantages in the conventional architectural education system and the small-scale practice: a) a flat learning curve due to complexity of interfaces and software itself, b) the requirement of additional education in software programming, scripting and advanced geometry. Consequently, it might be convenient to follow known and established industrial standards than to pursue a feedback method or parametric detailing (Reiser, Umemoto, 2006, Oosterhuis, 2003).

2.1. COURSE STRUCTURE

D.E.C.A.F. is not a design course, but instead focuses on the practical application of architectural digital engineering with complex geometries; in addition it examines this in the common small-scale practice in transition, referring to the ongoing shift in industry and architectural practice from traditional hierarchical building methods to parametric engineering. The main points of interest are BIM and CIM related issues, with respect to smaller budgets and resources and interactive design procedures. These issues cover in part approaches in group technologies (GT), manufacturing approaches, fabrication limitations and CAD-standards. Concurrently, other 4D planning methods, such as computer-aided process planning, manufacturing planning, automation planning, automated scheduling and similar automated output are discussed but not pursued in detail due to the practical limitations in the course layout (Schodek, Bechthold, Griggs, Kao, Steinberg, 2005).

The course explores subsequently 1) digital team-working, 2) RE as a hands-on example for exploring precision modeling and understanding digital assembly in conventional senses, 3) low-cost and low-input detailing and HS solutions to simulate small-scale practices and overcome general budget and time constraints and 4) RP as means of verifying detail solutions.

2.2. TRANSITIONS - UNDERSTANDING DETAILS

Much of contemporary architecture shows intention and interest in generating quasi-automatic forms and structures, genetic algorithms, and parametric design methodologies. They engage programming/scripting, setting inputs, initial conditions, controls, and performance; all of which are critical to an evolving form or structure or to produce a population of possible architectural phenotypes which are then selected according to extrinsic criteria or self-referencing. While Manuel DeLanda "once characterized this shift towards the genetic algorithm as the third wave of digital modeling software, one which would finally supplant all the previous identities of 'designer' and intentionality in favor of diagrammatic processes," it transgresses the question of authorship, and as a result, encoding, coupled with computer-controlled manufacturing, becomes a form of intelligent design for architectural life (Hight 2006). This formal expression stands in contrast with the approach of the practical operating architect; however has potential future relevance in the architectural practice. On the other hand, Karel Vollers builds a significant showcase for the practicing architect of how conventional industrial standards can be adjusted to match modeling abilities (Vollers 2001). It appears that both positions – the emergent-theoretical and the contemporary-practical - are critical to form a holistic understanding of a transitioning profession; therefore a selection of critical moments in architectural production and thinking, such as the work of Konrad Wachsmann and Frei Otto among others, has to be juxtaposed with contemporary, practical examples and evaluated to understand progress, stagnation and future potentials.

3. Team-Work

Another critical point in digital environments of architecture and engineering is the collaborative aspect and the seamless, lossless and precise exchange of large data-volumes between collaborators. Particularly in the small practice, a fluid process relieves redundancies and can reduce office overhead to a minimum. To simulate such conditions and to exemplify the relevance of creating digital hand-shakes in 3D modeling, students engage in an exercise of creating a singular surface out of two adjoining materials. This surface is randomly tiled, so that each student has to negotiate overlapping and continuous surface conditions with at least three other students. (Figure 1)

Parallel to this, students transfer the working data from 2D software to 3D software and reverse. RP systems are specifically used for immediate validation; these allow a) delivery working models and b) reduction of output costs; the sole purpose is to verify proposals and illustrate team-working successes and short-comings (Figure 2).

For a transitional approach between traditional design development and contemporary practice, concept modelers offer a significant positive solution: 1) software is accessible in terms of learning curve, immediate visual output and interface structure, 2) incorporated scripting tools and addons allow relative quick and solid transitions to other platforms of all categories.

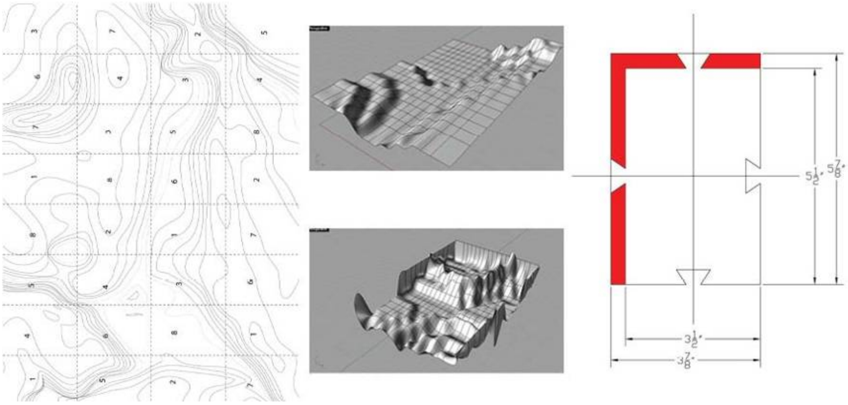

Figure 1. a) Original file for transformation into 3D; each student develops surfaces distributed according to tile numbers and is required to b) develop a topography with fluid transition to neighboring tile and c) negotiate a joining mechanism.

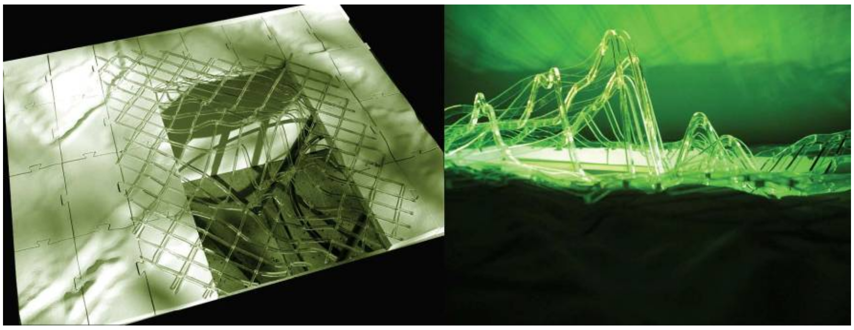

Figure 2. Composed end result made from two different materials and two different production methods joining together.

4. Reverse Engineering

In order to offer the best resolution in the surveillance practice, Reverse Engineering (RE) is brought into consideration. RE is a process describing recovery and/or discovery of technological principles of a mechanical, or in this case architectural, application through analysis of its structure, function and operation. The procedure further enables understanding of core-principles of generating ruled surfaces and their flexibility as well as applying those principles to fixed parameters derived from the studied object. RE further engages students in the practicality of advanced 3D modeling versus traditional paper output. Chosen objects further allow students to assess shortcomings in used software in terms of automation processes and limitations in semi-parametric modeling bundles. They are examined in teams in order to further critical thought in data exchange and data-matching.

3.1. REVERSE ENGINEERING PREMISE

Architectural Reverse Engineering differs from traditional RE procedures; while digitizers and 3D Scanners are in wide use for RE (Schodek, Bechthold, Griggs, Kao, Steinberg, 2005); the application is largely limited to relatively small objects, due to the make-up of the digitizing instrument. On a larger, urban scale, photogrammetric procedures are commonly the source for 3D city models (Kobayashi, 2006). The results can be grouped in various levels of detail and geometries are generally extracted from point clouds of aerial scans or local close range 3d scans, similar to efforts of the Geospatial Data Integration of the Integrated Media Systems Center at USC, Southern California (Knoblock, Shahabi, 2006). These point clouds are frequently turned into surface geometries in automated processes through proprietary software. The results are highly detailed, precise surfaces with photographic maps applied.

However, to achieve an RE model of an entire building, such methods would require disassembling of the structure and scanning the individual parts or adding of missing geometry to captured surfaces. Therefore the source of reference is construction documents and photographs.

3.2. OBJECT SELECTION

Three complex geometries have been selected for analysis: Frederick Kiesler’s Endless House in its 1960 version (unbuilt); Felix Candela’s Restaurant Mantiales in Xochimilco, Mexico, 1958-59; and the Malin Residence – commonly known as Chemosphere – by John Lautner from 1960. These projects reflect a non-traditional approach and irregularity in form, which makes it difficult to reverse engineer with common parametric, BIM supporting software. Rhino3D, a surface-modeler with limited parametric abilities, but a steep learning curve, is the preferred software for execution of these exercises.

In addition, the history of these projects allows students to engage in traditional building methods and requires accurate research on assembly methods and production of a precise 3D model that is easy to monitor through existing documentation. All three examples have also distinct building materials; Candela’s Restaurant Mantiales, represents an elaborate thin concrete shell structure where the main form, a rotated Hypar – hyperbolic paraboloid - challenges regular BIM approaches in reconstruction because of the absence of conventional wall/roof conditions. (Figure 3)

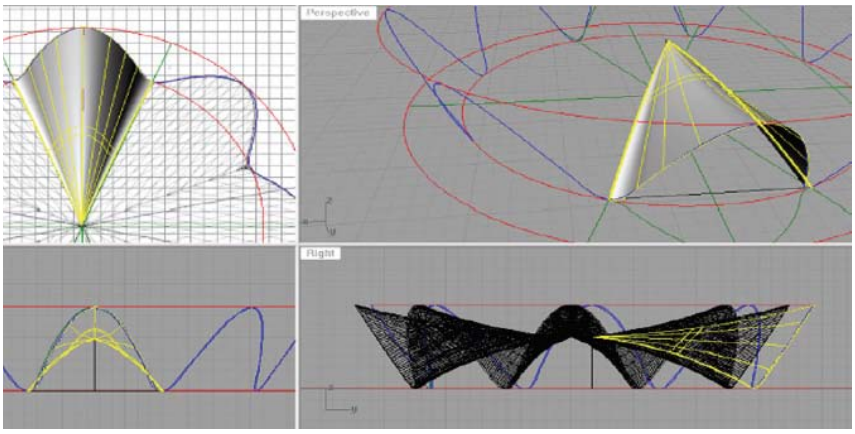

Figure 3. Deriving the Hypar from defining geometries. (Student: D. Rogers)

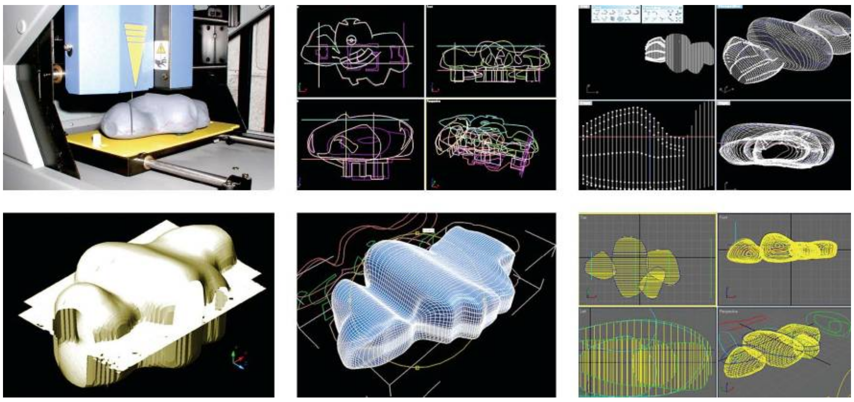

Figure 4. Reverse Engineering of F. Kiesler's Endless House various attempts from left to right: physical probe scans delivers due to undercuts in the geometry unsatisfying resolution (student: Zachary Smith); reverse surface manipulation in 3ds max, derived from outlines in order to create a homogenous surface is abandoned (student: Edwin Liu) in favor of a sectional, cellular approach lofted in Rhino 3D. (Students: Andrew Hernandez, Brandon Sakuma)

Similarly, Kiesler's Endless House follows in its bio-morphic structure a non-regular architectural form, which demands not only strategic modeling consideration, but also understanding of complex geometries in space. Both models were reduced to slightly simpler geometries in order to allow adequate time-management of the course.

The shape and irregular surface condition as well as the sometimes contradicting and sparse documentation of the Endless House represents a particular challenge. Tracing efforts to develop boundary curvatures and respectively cross-sectional shapes demand advanced modeling skills. Lofting of interpolated, equally spaced cross-sections within the traced outlines for individual pods provides satisfying results. The blending of the pod-shapes to one joint shape adds a level of imprecision and deprives the NURBs model of its initial flexibility; full parametric modeling, as offered through a Design Development Program might deliver a better accessible, malleable product (Figure 4).

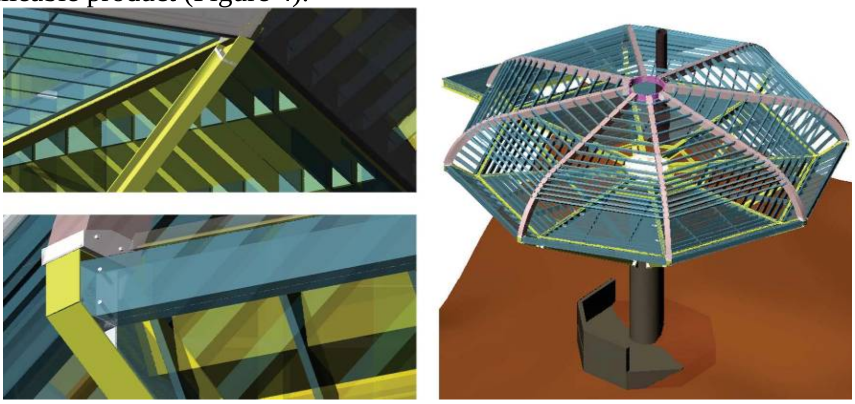

Figure 5. J. Launter, Malin Residence (Chemosphere) RE 3D model, details and structural skeleton (Students: R. Carr, D. Cunha, G. DelRosal, L. Fricke, M. Idoine, R. Machado, L. Shiri, J. Venzor)

Lautner's Chemosphere reflects another insight in the traditional building process: in contrast to previous RE examples, the Chemosphere is conventionally built but has an irregular form. The RE process points out several defects in traditional plan production. Through careful comparison of plan-documents and photographs as sources, conflicts occur in retrieving detailed information on geometry extracted from traced drawings versus written descriptions and missing specifications. The RE product is delivered with a high level of detail and is a result of interactive, dynamic team-work across various media (Figure 5). The traditional assembly procedure indicates a quicker and better solution under use of conventional Entity-Based Drafting Programs.

4. Output - Protocols

Given practical limitations and in order to investigate and manage architectural data in a more traditional sense, the course setting reduces scripting methods to a minimum. The importance of programming and respectively scripting is undisputed; programmability is a unique property of the digital medium. Traditional design methodology might be opposed by the exactness inherent to programming itself; though this concern was not reflected by the objectives of this course. In order to monitor and manage a critical surveillance, students are required to produce process protocols in the form of screen shots and notations. This simple documentation of procedures or problems enables students and the instructor to step into the modeling process at any time and examine successes, alternative approaches or errors in a dynamic and interactive fashion. Consequently students develop a method of discussing approaches and improving their software skills; protocols serve not only as documentation but also as step-by-step manuals.

5. Hot-Swapping Configuration

HS, a term borrowed from computer hardware jargon, describes a potential method which allows a) quick development of a base 3D model with enough flexibility and accuracy for future manipulation and b) exchange of construction methods up through a late stage of design and production. The re-association with fabrication, construction and affiliated practices is tied to the computational procedures. The previously reverse engineered digital model serves as base surface model and offers the conditions upon which material properties and structural methods can be exchanged in a timely fashion without the need for re-creating the geometries. In architectural education the tools are limited, and the understanding of architectural assembly is still a traditional one. Architectural construction methods are sequenced in accordance with the history of modernist, post industrial-revolution production, choosing pre-arranged certified techniques and using discrete building elements to form a hierarchical bottom-up sequence. These independent elements represent a simple nested hierarchy, easy to control in assembly and for its assembly schedule.

5.1. DESIGN METHODOLOGY

It appears that for an applicable generation of conditions which should allow a hot-swap of features, a parametric surface model provides the highest flexibility in a) establishing a controllable form and b) continually applying detailing features. This shows a significant shortcoming of Concept-Modeling Programs with a rather limited object history and suggests rather the use of a Design Development Environment, such as Microstation GC, Digital Project or ParaCloud for Rhino3D. For this investigation, it is necessary that current discussions concerning performative aspects of surfaces strictly follow the practical and not theoretical application, only to avoid unnecessary distractions from the objected goal. A reversed traditional approach of developing a structural grid and forming the architecture after its constraints would limit any flexibility in the exchange of generative methods. Any parametric surface can be treated as a field and therefore subdivided into elements, following a process similar to tessellation of digital surfaces first-hand. However, a structurally correct, generative tessellation would require specific scripting effort. The engineering-design application mainly focuses on a semi-realistic structural composite solution at this point (Figure 6).

Adopting the traditional method of tracing a digital line-drawing, a set of B-Splines and resulting 1/8 segments of NURBs surfaces for the Mantiales model are produced. To reconnect those after the rotational array is itself a transitional step; non-regular surfaces need to be inserted. Those transform a single surface ultimately into a polysurface, reducing the flexibility of the system as a whole. Afterwards, a cleaner surface can be derived through lofting of extracted sections and edges (Figure 7).

In both, Kiesler's Endless House and Candela's Restaurant Mantiales, various approaches in different complexities were repeatedly re-drawn to optimize the base model; these models received further manipulation through individual interpretations and considerations of structural systems through projections onto the surfaces themselves. These initial projections allow first analysis and re-application of different structural systems, which then, through simple sequenced processes of lofting and extruding, lead to rudimentary but applicable structural solutions (Figure 8a, b).

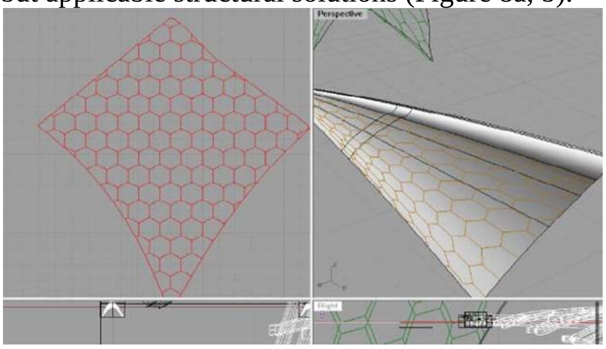

Figure 6. Example for pulling structure grids to a surface. (Student D. Rogers).

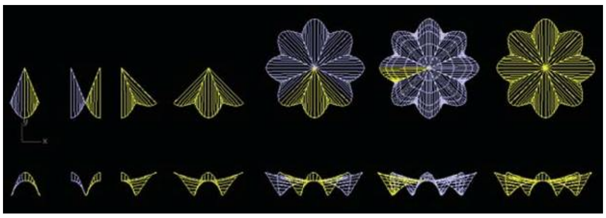

Figure 7. Completing the full rotational structure for the Restaurant Mantiales. (Student: M. Gonzales).

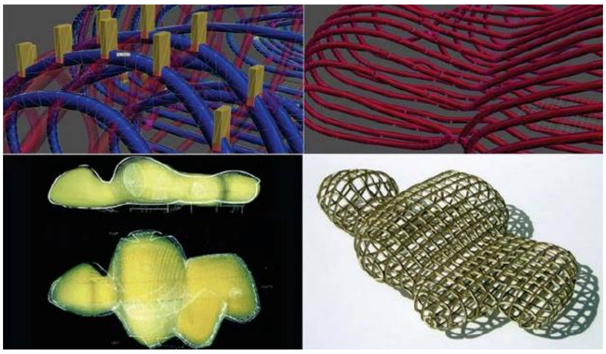

Figure 8a. Clockwise from top left: intersections between crossing members are derived manually, a time-consuming process, accuracy problems in intersected members in 3D, laser-cut structural model (production time incl. file preparation 50 hours) and accuracy overlay of drawing and CNC model (Students: J. Leong, E. Liu, H. Ming, A. Hernandez)

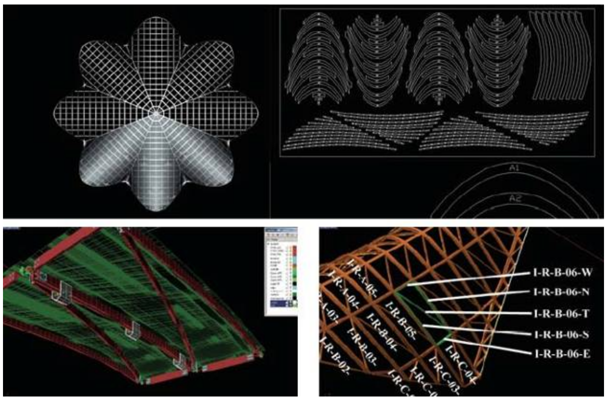

Figure8b. Clockwise from top left: finalization for production, creation of cut-sheets for laser-cutting (student: M. Gonzales), Tessellation approach and detailing including tagging of different elements (student: E. Scott)

Any additional, engineered input from this point on illustrates the limitations of modeling without scripted or fully parametric environments. Despite the maintained precision in the 3D model, corrections would occur manually and therefore in a linear fashion. This in turn can lead to human error and excessive time consumption.

The original assembly complexity of the Chemosphere offers multiple inconsistencies. In its reduced form however, the surface represents comparatively the simplest of all examples. A critical area is the transition of surface curvature from almost horizontal to vertical on the building edge. This forces students to generate an adaptive modular system with respect to changing geometry and structural necessity. The Chemosphere is reduced in appearance to accommodate for time constraints of the course, similar to other chosen study objects (Figure 9). Several HS attempts vary from creating rigid ruled surfaces to complex structural semi-automated scripts of Voronoi-assemblies (Figure 10).

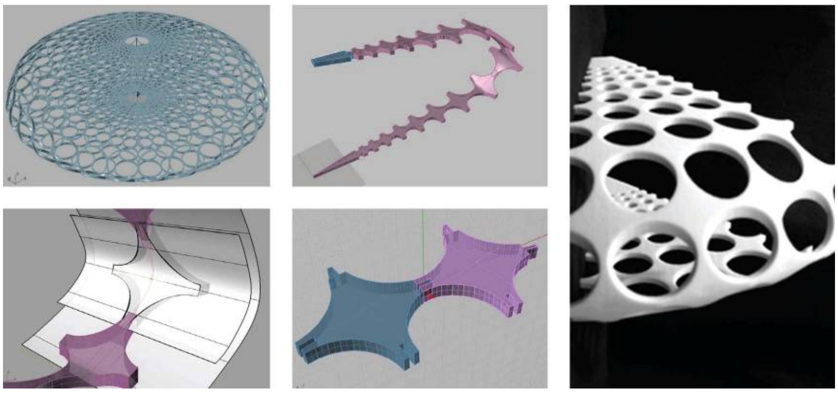

Figure 09. Sequence from production process starting in the upper left corner. Production manually developed (Student J. Venzor).

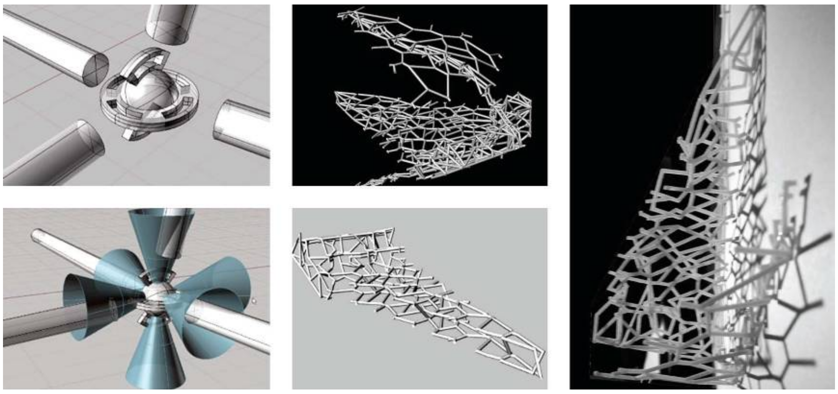

Figure 10. Voronoi structure imposed in original base constraints of the Lautner model Detailing principle developed manually, Voronoi structure scripted. (Student M. Idoine).

Conclusion

RE and the protocol system in conjunction with principles of HS provide students with understanding and armament to proceed in digital architecture in these times of transition.

The quality and level of resolution vary, but demonstrate that small scale projects can be executed without taking full advantage of real-time parametric modeling. The ability to offer a multiplicity of solutions – versioning – as result of HS in a relatively short time, allows affability in material and engineering negotiation (Figure 11).

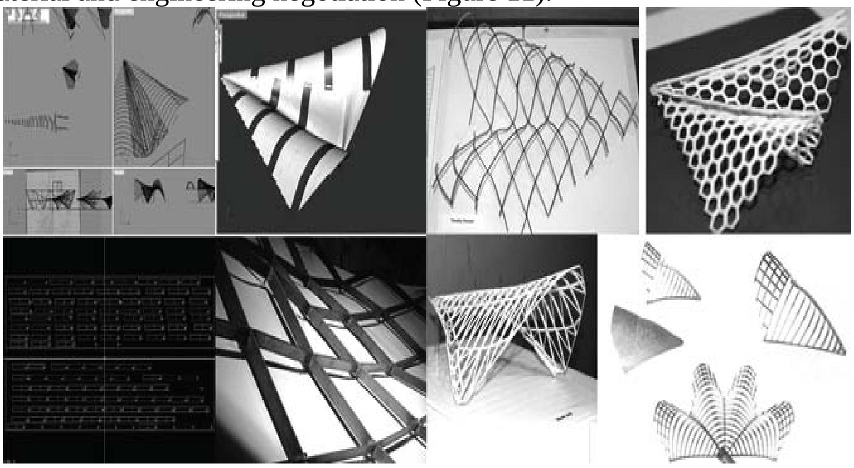

Figure 11. Clockwise from top left: different approaches with different Prototypes, shingled surface model with diagonally braced sheet metal frame (student: T. Vincent), hexagonal structure (student D. Rogers), cut-sheet for welding mock-up (student T. Vincent), tessellation model (Student E. Scott) and grid-lattice (student M. Gonzales)

Schedule, availability of technical support and architectural challenge remain key-factors for the competition of small architectural practices vs. large offices; Real-time HS as a technique remains, despite improvements in modeling accuracy and software advancement, a prerogative of designers with adequate programming skills and education. Kilian points out, that real-time events require programming of such so that the computational incident takes place during its calculated execution. (Kilian, 2000). Common affordable and available software packages currently do not provide this commodity in forms other than indigenous scripting languages or related Feature-based Environments; scripting itself supports customization of software which does not inherently support enough flexibility in its command structure. This solution can therefore be seen as a reverse approach itself. Software designed for architects such as Entity-based Drafting Programs are geared toward implementing industry standards rather than generating a desirable, malleable tool for architectural design. Hence, educators are frequently forced, rather to comply with standards, initiated by software producers and industry, than to represent a contributing element to the industry itself. The methodologies of RE can only contribute to an understanding and provoke alternative thinking methods. Comprehensive knowledge of engineering, industrial production sequences, explicit computational and geometric training, simplify the architectural and respectively digital production process. It would further allow architectural academic structures to regain its position as informant-educator. Through RE, students gain limited but valuable insight in the traditional application of architectural assembly integrated in the course sequence and may as result initiate different economies in production.

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