By Any Means Necessary: Digitally Fabricating Architecture at Scale

ABSTRACT
Architectural manufacturing is a balancing act between production facility and a custom fabrication shop. Each project Zahner takes on is different from the last, and not likely to repeat. This means that workflows are designed and deployed for each project individually.

We present Flash Manufacturing, a fabrication methodology we employ in the production of architectural elements for cutting-edge and computationally sophisticated buildings. By remixing manufacturing techniques and production spaces we are able to meet the novel challenges posed by fabricating and assembling hundreds of thousands of unique parts. We discuss methods for producing vastly different project types and highlight two building case studies: the Cornell Tech Bloomberg Center and the Petersen Automotive Museum. With this work, we demonstrate how design creativity is no longer at odds with reliable and cost-effective building practices.

Zahner has produced hundreds of seminal buildings working with architects such as: Gehry Partners, Zaha Hadid, mOrphosis, Herzog & de Meuron, OMA, Steven Holl Architects, Studio Daniel Libeskind, Rafael Moneo, DS+R, Foster + Partners, Gensler, KPF, SANAA and many more.

This paper disrupts conventional discourse surrounding manufacturing/construction methods by discussing the realities of mass customization—how glossy architectural products are forged through ad hoc inventive engineering and risk tolerance.
INTRODUCTION

Zahner has fabricated architectural elements for more than 120 years and has utilized digital fabrication techniques on large-scale buildings for more than 20 years. From this work we have developed a breadth of experience on the trials and tribulations of delivering unique buildings. Taking on many of the world’s most complex architectural projects requires us to develop and deploy a diverse set of tools (both hardware and software) to match the expanding requirements and ambitions of architectural projects.

Advances in computational design tools directly impact our work, on both our means and methods and the projects brought to us by a new generation of computationally sophisticated designers. Zahner continues to pioneer the incorporation of manufacturing methods from disparate fields (Pro/Engineer, Digital Project, Dassault 3DX) to solve engineering and fabrication challenges (Kolarevic 2003; Glymph 2003). Through this process of appropriation and deployment we have become experts in not only creating custom projects but also in generating unique project workflows. Instead of focusing on a singular fabrication process or machine (Vasey et al. 2015; Aejmelaeus-Lindstrom et al. 2016), this paper describes an approach for mixing and matching production strategies and infrastructure on a per-project basis.

Realizing the widely varying, intricate, and complex visions that make up modern architecture, however, also means that we need widely varying and, at times, complex manufacturing methods. Flash Manufacturing presents a solution for constantly changing fabrication specifications. We incorporate agility in the form of modularity and reconfigurability at each stage of the production process, from CAD to CAM, to custom machine and end effector development, to shipping and assembly instructions. Many of the perceived hurdles in fabricating geometrically intricate architecture such as tooling, CAD/CAM workflows, expense, and schedule can be countered with Flash Manufacturing. Our goal is to demystify parts of our process, dispelling the myth that shape is complex and perilous, while banality is simple and safe. We hope to shed light on the endless possibilities available with a collaborative design to fabrication process.

In this paper, we present the case studies of the Cornell Tech Bloomberg Center and the Petersen Automotive Museum, highlighting subtle but salient workflow innovations that enabled their production. We conclude with thoughts on future work.

BACKGROUND

Digital design and construction has become commonplace within the Architecture, Engineering, and Construction (AEC) Industry. Form generation has never been easier thanks in part to the ever-expanding options and accessibility of high fidelity CAD modelers. On a jobsite today one can see HVAC contractors scanning interiors and creating coordinated 3D models, real-time grade control on excavators, and even LIDAR-equipped drones providing built point clouds mid-construction. Revit turns 17 this year and has solidified itself as an AEC standard for building information management by expediting drawing creation, project documentation, and delivery (Day 2017).

The Broad Art Museum is evidence of what a fabricator like Zahner can achieve when paired with a computationally savvy design team. Today’s tools are extending the reach of architects and engineers, increasing what’s possible for small teams. A recent presentation by Zaha Hadid Architects and Front Inc. described the production of 1,212,637 unique parts for the Morpheus Hotel by a team of four people (Levelle et al. 2016). This ability to produce more with less, along with the increasing accessibility of inexpensive CAD software, foreshadows an exciting future for the built environment.

Mass customization remains difficult and high risk for manufacturers because economies of scale are not present for low volumes, and the ability to spread setup costs over large production cycles does not exist. Custom architectural production is fast paced and budget constrained.

While a lack of volume makes production challenging, it also provides opportunities via less strict processing requirements and reduced production penalties. Production errors are not penalized in the same way as mass manufacturing, precisely because initial investment is low and quantities are smaller. This allows for impromptu tests to happen in step with production, and optimization strategies can be deployed as they are developed.
When considering Kieran Timberlake’s Law of Economy and Scale (Figure 2) and how it might be upended, we propose a hybrid software and hardware strategy as a means of shrinking costs and speeding delivery (Kieran and Timberlake 2004).

Today our software tools allow small teams to tackle large projects efficiently, increasing scope while lowering engineering costs. Custom automation tools developed in house allow Zahner’s team of ~30 engineers and architects to manage nearly 100 projects simultaneously.

While design and computation tools have revolutionized how architects work, the transition from design to fabrication is still serpentine and arduous when done at building scale (Coleman et al. 2016). As AEC software developers look to the future, developing cloud-based applications and interoperable software, their trajectory speaks to the nature of our industry’s nonlinearity and the diversity of project inputs we see daily (Day 2017).

METHODS
Making and Managing Lots of Parts: Software Automation

While each project we take on is unique, a few constants exist between projects. Most architectural projects are too large to transport as a single unit because buildings don’t fit on roads. This means the first step is the sectioning of the project into shippable units.

These shippable units are prefabricated in our factory and will only be fully assembled at the final construction site. Because of this, there will be no complete fit up of the parts before arriving on site. To ensure compatibility between parts and to verify we deliver the exact geometry defined by our clients, over 90% of the parts fabricated in our shop are on Computer Numerically Controlled (CNC) cutting devices. To fabricate a part on a CNC machine there must be a digital definition of each part and a series of support documents. These part definitions range from fully articulated 3D models to a few lines of code. Digital fabrication is a natural ally of mass customization because it’s "killer app” is the production of one-off parts, products, and for us, buildings (Gershenfeld 2012).

Our software strategies are informed by a long history of interacting with digital fabrication machines and a plethora of CAD/CAM software. Our early experience on projects like the Experience Music Project (now MoPOP) or the Massachusetts Institute of Technology’s Stata Center, both designed by Gehry Partners, catalyzed our shift away from paper documentation
and the utilization of coordinated digital models (Kolarevic 2003; Glymph 2003).

With many parts comes lots of information. A single part may have 5 to 10 supporting elements (models, drawings, assembly instructions, etc.). For example, a project with 50,000 parts may have upwards of a quarter to half a million elements. Quantities like these make paper design and documentation impossible. For this method to be successful our process must be 100% digital from documentation to fabrication. A fully digital process allows for opportunities in managing information and enables the handling of more sophisticated geometries and assemblies because variation is not penalized (Kolarevic 2003; Glymph 2003). Our last step before fabrication is the conversion of part definitions into machine readable formats using both custom scripts and CAM software.

A reciprocal relationship exists between the logic of our parametric models and our means of fabrication. We incorporate material and machine limitations into our parametric models, ensuring our digital representation of a project is coordinated with the physical world. As a production process is defined, inputs and outputs of the model are shuffled and recombined to accommodate the production requirements. This means that the agility of our computational process must be mirrored in our production strategy, reinforcing the need for custom processes.

**Augmented Processes and Multipurpose Machines**
The design of most large-scale digital fabrication machines aims to serve a specific industry and/or is based around producing a particular kind of part. We utilize many of these specialized machines because it is not economically feasible to purchase or design a custom machine for each of our unique applications. Because our parts vary widely, we are often operating at the edge of our machines’ specified functionality. We are consistently modifying, hacking, and “tricking” production machines into performing tasks the machine manufacturers never intended or anticipated, essentially “misusing” machines (Coleman 2014).

Custom-applied engine-turned stainless steel (Figure 3) is an early (1990s) example of an augmented and ad hoc fabrication process. Engine-turned stainless is applied by pressing a spinning abrasive pad or wheel systematically onto a sheet of stainless steel. The resulting pattern is a series of overlapping circles with distinct reflective properties. However, a custom or image-based pattern would require a very time-consuming layout process or a means of motion control. Zahner accomplished custom patterns by co-opting the motion control system of our turret punch press. Instead of punching with the machine, it was used only to move the sheet in X and Y directions. A magnetic drill was then attached to the side of the machine and used to abrade the surface (Figure 5).

The punch was programmed with the desired pattern, and as the machine reached each position, the operator pulled the handle on the drill, lowering the spindle to contact the surface. While hardly an optimized, or exciting, process for the operator, the energy and expertise necessary to augment the machine was much less extensive than incorporating the drill into the
machine’s control system. This recombination tactic is an example of the minimal setup targeted by Flash Manufacturing. For projects with small quantities, ad hoc process augmentations are a direct means of achieving the target with small investment.

The turret punch in the prior example is a task-specific machine designed to punch holes and form metal sheets. The punch was never intended to apply finishes to sheet metal, and thus needed to be augmented to do so. Today we deploy a more advanced version of process recombination and augmentation with the help of industrial robot arms. Unlike task specific machines, industrial robots have ambiguous application specifications and are essentially multipurpose tools. Changing the end effector on a robot immediately changes its functionality while maintaining the same programming logic. In factories, robots perform repetitive tasks for hundreds of thousands of cycles, but the variety of tasks robots perform is very limited. Typical tasks include palletizing, spot welding, assembly, painting, etc., and once programmed, they are dedicated to the specific operation. Robotic arms can perform a wide range of precision tasks, but much of the potential is never utilized.

This additional functionality is the reason robotics are an important tool in our process. Robots are flexible by nature, “generalist” machines capable of performing a diversity of tasks—the inverse of task-specific machines. When combined with sophisticated software able to batch-process robot instruction files, their full potential can be realized. In the following case study of Cornell Tech, we utilized robotics to accomplish hundreds of thousands of individual tasks by taking advantage of their versatility. Augmented processes are most successful with machines that are extensible and provide a flexible/open programming structure.

FLASH TOOLING

3D printing or additive manufacturing has been around for nearly 3 decades in varying forms and materials. Today, we are seeing a change in how the output of these machines is being used. Instead of printing part/product prototypes that are later translated into a production process, 3D printers today can produce functional parts. The fast turnaround of functional parts and inexpensive material make this technology well suited for a highly variable production environment like that of Zahner. While limitations in strength and performance exist for parts produced via fused deposition modeling (FDM) due to anisotropic characteristics (Tam et al. 2016), we have found ways to exploit these limitations. We use 3D printed parts for robot tooling, jigs, and quality control instruments to support custom fabrication processes with short lead times and low costs.

The nearly complete Cornell Tech Bloomberg Center, designed by mOrphosis Architects, on Roosevelt Island, is a result of a highly custom design to fabrication process. Nearly 100,000 ft² of cladding on the building is composed of robotically fabricated aluminum panels. Each 2’ x 10’ panel contains 125 tabs, robotically turned to specific orientations. The result is a “Textured Façade” (Martin, Coleman, and Kwong 2017) with dynamic qualities due to both the individually rotated tabs and the application of color shifting paint (PPG Vari-Kool). During a “Design Assist” period we worked with the architects to craft a novel design to fabrication process for the project. This included the development of innovative geometric, software, material, and machine strategies. Through the production of numerous full-scale mockups (Figure 6) we developed an image-based method for encoding rotation angles and grid spacing within an automated production scheme.
The ~4,000 aluminum panels vary in size and shape from rectangular panels, radiused forms, and brake-formed corner elements. Roughly 90% of the panels have a 5 x 25 grid of 3” circular discs punched into the faces (Figure 9). The result is a matrix of circular discs connected to the remaining panel by two tabs on opposite sides of the disc. The tabs act as an “axle” from which the discs can be rotated. Prior art using this technique includes the 2009 Solar Decathlon entry and Lumen House by Virginia Tech, fabricated by Zahner.

We recommissioned a FANUC i2b welding robot arm to rotate each of the nearly half million tabs to individual angles. The rotation was accomplished with simple point-to-point maneuvers, mapping toolpath depth to disc rotation. The toolpath for turning the discs was intentionally kept simple, with no multiaxis maneuvers (>3 axes) to ensure that the task could also be accomplished with a cartesian robot for production flexibility and for ease of program verification.

We developed a small chess-pawn-sized tool contoured to fit in the cavity between tab and panel created during tab rotation. This tool was printed on a Makerbot Replicator 2 in PLA plastic and designed to be a sacrificial element in the process. If unintended contact occurred during the tab turning process, the pawn was designed to break in lieu of the panel or robot. This is an important consideration because the robot would be performing unique tasks on every panel with no “dry runs.” The 3D-printed parts took only hours to create and could be...
replicated/optimized with virtually no cost or interruption to the fabrication process.

We developed a single automation routine to produce all the fabrication drawings, machine code, robot code, and quality control documentation simultaneously. This was accomplished using the software Rhinoceros3D and plugin Grasshopper, custom Python, and C# components. The software workflow we developed consisted of importing 2D-building elevations from Digital Project with panel boundaries and disc center points, assigning rotation values for each tab from source images and, finally, outputting fabrication files and robot code directly to the machine.

The Cornell Tech building is an exemplar of a flexible production scheme that utilized a recommissioned robot, inexpensive 3D-printed robotic tooling, and lightweight software to produce a one-of-a-kind architectural project.

Robotic Adhesive Delivery
Often construction schedules do not allow for the preconstruction “Design Assist” work discussed on the Cornell Tech project. Under these expedited conditions, production strategies must react and change on the fly. The ideal sequence of design to fabrication is often “disrupted,” making process flexibility and agility crucial to success.

On a current project, mid-construction design changes to panel buildup required us to react with extreme haste. The changes required us to apply structural adhesive to ~1,000 panels, with positional tolerance of +/- 1/16th of an inch. Each panel required 126 uniquely placed beads of adhesive, making for ~126,000 beads total. The precision, schedule, and quantity required made this application a good candidate for automation.

After the success of 3D-printed tooling and Grasshopper workflow on Cornell, we applied the lessons learned to this robotic process. We had one month to design, test, and deploy, so the core criteria for the dispensing tooling was short lead times and rapid integration. We again recommissioned the same FANUC i2b welding robot arm to accomplish the precision dispensing. The 3D-printed armature needed to connect the dispensing equipment (valves and solenoids) to the end of the robot. Like the prior example, the armature was designed to structurally fail without damaging the robot, dispensing hardware, or architectural panels. The part was printed on a Makerbot Replicator 2 in PLA and contained a flexure capture which held the dispensing head. Three iterations of the end effector were designed, fabricated, and tested over the course of three days, with the final iteration deployed into production. This rapid design-to-deploy strategy was critical to the success of the project and emphasizes the need for ad hoc, improvisational techniques as a producer of custom architectural products at scale. We are disrupting industry standards of long lead times.
and inflexibility with the remixing of advanced technologies like robotics, 3D printing, and custom software.

Integrated Workholding/Fixturing
As discussed earlier, it is not economically feasible to invest in robust infrastructure for every project. This has a large impact on how we create and fabricate parts. It also impacts the way we handle and assemble products, namely our jigs and fixtures. A production facility that makes many of the same product will work to streamline the movement of material and minimize the effort of its workers. Equipment that enables the easy movement of parts from one place to the next, like trolley conveyors and monorail tracks, reduces effort related to material manipulation and specializes the production line. For example, a conveyor belt system will have a maximum load it can handle and limits to the size of part it can carry.

Our factory has the unique challenge of handling production volumes without the equipment used in mass production. While this requires additional effort in material handling, it also means we are not constrained to any shape or size of unit. As with our software and machine reconfiguration, mass customization has required us to be inventive with our assembly and material-handling strategies. Because we are not beholden to preexisting material-handling infrastructure, we can meet vastly different project types and requirements. We have handled parts as big as 70’ x 9’ x 8’ (Figure 11) and as small as a single folded skin panel. The following case study of the Petersen Automotive Museum demonstrates the important role of flexible material handling and assembly in a complex project.

The Petersen Automotive Museum
Zahner recently completed the engineering, fabrication, and installation of the renovated Petersen Automotive Museum in Los Angeles, designed by KPF. The renovation included a veil of doubly curved stainless steel ribbons stood off the building’s surface by a complex system of outriggers. Each of these unique ribbons ranged in size from 4’ to ~45’ long with a continually morphing cross section.

Each ribbon is split into sections composed of a curved central steel pipe with anchoring “boots” at either end. Waterjet cut aluminum “shark fins” make up the substructure of the ribbons, which are attached along the length of the pipe. The aluminum fins are waterjet cut to the exact profile of the ribbon and are what control the overall shape. Stainless steel and painted aluminum skins were then attached to the assembled aluminum substructure. Each ribbon was assembled from more than 100 unique parts before being shipped to the jobsite and attached to the steel superstructure of the building.

The required tolerance between skins on the Petersen Automotive Museum presented several engineering challenges during design and fabrication. The production of numerous full-scale mockups proved that achieving the specified tolerance between skins was impossible with our typical methods for...
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discretizing advanced geometry. The fabrication tolerance of the curved steel pipe was too large to successfully attach the CNC-cut stainless steel skins. We required a new method for orienting the skins on an inaccurate pipe. The four-sided ribbons presented additional challenges beyond the ribbons’ complex geometry because the skins were self-resolving, with no “back face” to attach to or absorb tolerance.

Our solution was to detach the substructure and skins from the curved pipe member. This “floating skin” approach allowed the pipe to deviate from the design without affecting the skin shape or placement. This approach was accomplished with workholding that established the tube ends at a known position with respect to a ground plane. Each interior “shark fin” was then produced with an integrated positioning jig that oriented the fin in 3D space with respect to the ground plane and pipe ends (Figure 13). The void space between the pipe and the shark fins absorbed dimensional deviations of the pipe. The final attachment of the skins to the unsecured “shark fins” set the roll and pitch orientation of each fin. Once oriented, the “shark fin” was secured to the structural member. By coordinating the assembly jig as a part of our parametric model, it allowed for a high-tolerance part to be attached to a low-tolerance structural member.

Because we are not bound to specialized means of material handling and assembly, engineering solutions can be found even at late stages in our process. In this case, the assembly jig was a foundational part of the process and the linchpin of our design and construction methodology.

The holding jig provided a known position for each ribbon during our assembly process. Once complete, those known positions could be used for 3D nesting for shipping (figure 15). Once on site the holding jig had its final role as the rigging from which it could be hoisted into place. An extremely complex element like the Petersen ribbons hinged on an assembly and material handling technique, an opportunity only available with a well-executed parametric design to fabrication workflow and flexible assembly strategy.
RESULTS
To work as a fabricator of complex architectural projects, we've had to develop an agile production strategy that shifts and responds to varying project requirements and ambitions, described here as Flash Manufacturing. This approach of remixing software and hardware has led to the production of many sophisticated buildings, and as computational design advances, further opportunity exists.

The Cornell Tech Bloomberg Center showed how lightweight software, extensible machines, and 3D-printed tooling can deliver a truly unique façade. The Petersen Automotive Museum demonstrates how a lack of definition in our material handling and assembly process can offer engineering solutions when combined with a robust computational strategy.

CONCLUSION
While Zahner has been able to deliver many fantastic buildings with the principles of Flash Manufacturing, it is laborious and risky. The AEC industry is a tumultuous, fast-changing landscape of requirements and competing priorities. It is difficult to dedicate resources, whether physical or digital, in any one direction without risk of wasted or redundant effort. Proprietary software and inextensible hardware makes deploying custom processes difficult and dictates predefined workflows. Even when a machine is capable of being modified, poor documentation of the hardware and programming logic makes interfacing in non-prescribed ways nearly impossible. We are currently working with machine manufacturers to change this paradigm. We hope to demonstrate the benefits of providing open APIs and reconfigurable hardware to their customers by showing that custom can be standard.

Zahner’s R&D team is working to make Flash Manufacturing even flashier by pursuing “building blocks”: production blocks that are multipurpose, reusable, and interoperable, making custom applications easier. Two examples of blocks are universal machine control, which standardizes the ways we interact with our tools and removes black boxes from our process, and modular hardware that can be swapped and reconfigured at a moment’s notice with little more than a wrench and a multimeter. With these new resources, and a few others, Zahner is poised to dramatically expand what is possible to build.

The projects presented demonstrate that unique buildings require custom workflows. Zahner exists in a balancing act between mass production and custom fabrication because our projects are composed of high volumes of parts and do not repeat. This has required us to develop a flexible production strategy to accommodate the ambitions of a diverse range of designers. Our shop is reconfigured daily to match the capabilities of our computational tools and demands of our clients. Our campus is littered with mockups from hundreds of projects and experiments, each an empirical test to be scrutinized and inserted into our workflow.

Disruption is our status quo.
ACKNOWLEDGEMENTS
Completeing a stunning building is a cumulative effort of numerous, talented individuals. From the designers to the field crews putting in each and every screw, Zahner acknowledges its contribution is just a part of the enormous effort it takes to create something special. Thank you to those who make it all possible.

REFERENCES


IMAGE CREDITS
Figure 3: Eli & Edythe Broad Art Museum by Zaha Hadid Architects. Photo Credit- Iwan Baan.

Figure 8: Cornell Tech Bloomberg Center, under construction. Photo credit- mOrphosis Architects.

All other drawings and images by the authors.

James Coleman currently acts as Lead Research and Development Engineer at A. Zahner Company. He is involved in projects as a digital design and manufacturing specialist. James holds master’s degrees in architecture and mechanical engineering from The Massachusetts Institute of Technology. His current research is centered around parametric design-to-fabrication workflows and one-off automation strategies.

He has worked internationally as design engineer for architectural projects of a variety of scales and also as a Product Development Engineer at the Ford Motor Company in Dearborn, Michigan. With diverse set of fabrication equipment, industrial robots, and custom made machinery James makes things, breaks things, and invents things with varying levels of success and sophistication.

Shannon Cole is an Engineering Manager at A. Zahner Company. He is a licensed professional engineer, and holds a BS in Architectural Engineering from the University of Kansas. He enjoys the challenges of searching for systematic processes in the unique designs, and exceeding the expectations of some of the industries most sophisticated customers. He is actively seeking a better career description than “makes weird stuff from sheet metal.”