Visualizing the Operative and Analytic: Representing the Digital Fabrication Feedback Loop and Managing the Digital Exchange

Kevin R. Klinger and Joshua Vermillion
Digital architecture is process-based and reliant upon a conversation between digital visualization, analysis, and production. With the complexity of information generated in process-based digital practices, we need to effectively manage and exchange the information. Feedback loops are integral to this process/product, and thus require extensive management of complex versions of visual and data related information. Quite a lot of scholarly attention has been focused upon highlighting innovative projects using digital fabrication and serial customization. However, there is a scarcity of scholarly work about innovations in visualizing and representing the design data integral in this feedback loop. This paper will examine innovative representational devices such as the matrix, sectioning, layering, bracketing, nesting, and other new forms of organizing, visualizing, analyzing, and simulating complex data, intent upon communicating multiple levels of operations during the design and fabrication process. With a rigorous taxonomy of operative and analytic devices for process-based digital design development, we can begin to outline a trajectory for future evolutions in practice. This writing is an attempt to make a few steps in this direction, and demonstrate some of these new representational ideas in practice.
1. INTRODUCTION

No doubt, digital technology is rapidly changing the way architecture is designed and made. Digital technology has been absorbed more thoroughly in other disciplines such as industrial design; and some processes, ideas, and techniques have been imported into innovative architectural practices from the computer programming, biochemistry, automotive, aerospace, and other industrial manufacturing communities. Presently, architects are able to employ software to build entirely digital models of a project, through conception, final design, and fabrication of the building components. These “master” models, in turn, can be used for managing the assembly and construction of the final systems. Architectural components can be parametrically modeled, computationally analyzed, digitally fabricated, and accurately assembled with the same digital master model. Each phase of the project development revises the modeling information and through this digital exchange advises all of those involved with the project. The digital master model works in concert with analysis software, NC technology, bar coding, GIS systems, and other technologies [1-3]. In this way, the digital master model is the constantly evolving database that drives all of the design and production processes for an entire project—the center of a complex digital exchange between all of the building industry agents responsible for designing, engineering, making, assembling, and managing the structure.

As the computer increasingly plays a key role in the translation of information for computational analysis and digital fabrication, new questions arise challenging the specific tasks of the designer as well as the entire building enterprise. Not only has digital technology allowed us to design with different formal strategies, requiring new ways of thinking about architectural “principles”, but devices used to analyze and fabricate are influencing how we design for performance and constructability. In fact, these devices become an important part of the digital exchange. Both the ways in which we think about architecture and the instruments and techniques we use to make architecture are changing dramatically. Another way to think about this is that we have finally conceptually arrived at a new form of “Architecture Machine,” only slightly different than the one suggested by Nicholas Negroponte in his seminal book by the same title over 35 years ago at the dawn of computing in architecture [4]. Today, it is useful to consider ideas similar to those outlined by Negroponte by first examining how we visualize information throughout the process of experimentation and production in making architecture.

Digital architecture relies on an iterative and seamless process-oriented design development. Computational analysis and digital fabrication/rapid prototyping allow architects to test, analyze and build prototypes more quickly and with greater accuracy. Feedback loops are integral to optimizing and realizing this process/product [5], and thus require extensive
management of complex visual and data related information. Innovations in visualizing and representing the design data are essential to understand the feedback loop and facilitate designers making critical informed decisions. Representational devices such as matrices, sectioning, surface analysis, nesting, unfolding, simulation, and bracketing reveal relationships to be considered throughout the project’s development, and serve as visual feedback during this dynamic design process. The importance of visualization, while helpful in communicating design intent, is a direct result of an engineering and production necessity for the cut-out of the 2-d sheet, the warp of the 3-d tool path, or the structural requirements [6] for digital production.

Branko Kolarevic argues: “the need to externalize representations of design, i.e. produce drawings, will lessen as a direct consequence of the new digital possibilities for producing and processing information” [7]. Nonetheless, visualization needs are shifting to facilitate different forms of production, albeit more on a design decision-making level. We need to carefully consider emerging forms of visualization for computational analysis and digital fabrication that communicate, not on the perceptual/representational, but on the performative and the operative. In some ways, this kind of visual communication is intended as much for the machine as for its human counterpart. In fact, an important distinction is made by Sharples, Holden, and Pasquarelli (SHoP) [5] when they discuss this division in the perceptual visualization process from the versioning (and fabrication) process—the latter process yielding an emergent solution through the continual addition and management of site, program, performance, design, and material production constraints. In this case, a prototype is not seen as a final, standard product, seemingly frozen in time and ready to be mass-produced, nor the simple realization of one a priori idea [8, 9]. Constraints facilitate the process of cumulative selection [10] from which an infinite set of possibilities are narrowed down to a finite set of solutions that optimize effect, performance, and economy, therefore necessitating the visualization of these constraints. The new forms of visualization resulting from simulation and digital fabrication are more akin to scientific visualization cultures such as medical diagnostics, or even the traits of medieval stonecutters [11]-instructions for communicating the fabrication geometry rather than any spatial geometry. This kind of visualization is more interested in tolerances and performance, and in productively feeding back to revise an iterative design strategy.

2. REPRESENTATION + EXPERIMENTATION FOR FUTURE CONSTRUCTS

In the late 20th century, prominent “paper architects”—those known primarily for their ideas and proposals, rather than completed buildings—relied heavily upon experimentations in representation. A number of these
“paper architects” (such as Daniel Libeskind, Zaha Hadid, Rem Koolhaas, Peter Eisenman, Thom Mayne, and Bernard Tschumi, et al.) are now actively engaged in building, and demonstrating that experimental representation methods they used in the past are directly informing their design processes in their built work.

Similarly, digitally-driven architecture today is engaged in serious experimentation that suggests promising new directions for the future of architectural design. Innovative representational devices are evolving which allow new forms of organizing and visualizing complex data—a necessity for directing machines to follow multiple levels of operations during the fabrication process. These representations inform the design process as feedback for new design iterations before final fabrication. The majority of digital fabrication projects are broadly being realized as small scale interventions and experimentations and slowly shifting into large-scale constructs. It appears to be the first few steps in a broader shift in practice. Once the process of this interaction becomes clear to the designers, we see a shift in scale applying the same principles. Consider today the movement of SHoP Architects in New York City in just a short few years from a digital fabrication installation at PS1, to multiple condo units with digitally fabricated building skins, to the master planning of the East River in Manhattan. Only now are we beginning to realize the full capacity of these technological principles to orchestrate architecture’s impact at the urban scale.

3. CHANGING PRACTICES REQUIRE CHANGING PROCESSES

Innovative fabrication techniques (and the processes of manufacturing various building components), which were once considered at the experimental edge in architecture, are becoming more commonplace and, as a result, are questioning the methods and organization of architectural practice. As young, innovative firms such as SHoP and Foreign Office Architects have demonstrated, digital technology is an essential tool that allows designers to manage the digital exchange—the “conversation” between players involved with design, visualization, and production—in a bottom-up, collaborative manner. These innovative firms participate in the total process of design and fabrication to produce sophisticated, complex solutions resulting from the negotiation of design, site, performance, and manufacturability constraints. This is a significant indicator of the power of computation in design—a process that folds material and technique with site, environmental, programmatic, and cultural parameters, etc., thus creating a digital model from which all relevant information can be quickly and easily extracted. With this process-based design development rigor, form evolves out of feedback by negotiating the input parameters; form, as a result, is well informed. Once the design information is ready for translation from...
“informed form” in the model into a physical form, the digital files used to generate the project are prepared for driving the fabrication process. All of the steps from the initial parameters, through the feedback, and into translation require different means and methods to visualize and encode the information of the project. The key to understanding new processes from practice is to interrogate the representational strategies for communicating the design information to the humans and machines responsible for making and assembling the project.

The cladding of the Porter House Condominium, by SHoP Architects, is an example of innovative process-based methods in practice. Precise information was fed directly into a powerful laser-cutter to fabricate the zinc panels that make up the building’s custom curtain wall system. The architects created a smooth transition between the design and the fabrication process, were aware of all relevant design information and input parameters, and eliminated the need for typical shop drawings while maintaining a more active role in the realization of the final construct.

Varying degrees of fabrication are deployed in SHoP’s innovative projects. The Camera Obscura, Greenport, NY, is a 100% digitally fabricated project. Rather than using the traditional plans, elevations, and cross-sections to explain how to assemble the building, SHoP used three-dimensional exploded diagrams directly generated from the computer model to explain where each assemblage was located in order to facilitate construction (shown in Figure 1). At the 2003 ACADIA conference at Ball State University, partner Chris Sharples [12] likened the component assemblies of the Camera Obscura to a scaled-up model airplane kit.
Technologically driven change has always been a catalyst for new ideas in architecture, and today, digital technology is the key agent for innovation in design and construction processes, driving the convergence of representation and production information, a point observed early by Branko Kolarevic during the nascency of digital fabrication techniques in architecture [1]. Thus, to enable evolving innovative practices today, we need to rely upon effective means for the digital exchange of information.

4. OPERATIVE + ANALYTIC REPRESENTATION

Many examples of operative and analytic representation already exist, providing the basis for the formative assessment of a project's spatial effect, performance, economy, and efficiency of production throughout design and fabrication. In order to facilitate a broader understanding on how these tools are used in contemporary practice and education, we have organized contemporary examples of operative and analytic representational techniques into three broad categories—force analysis, production analysis, and complexity management.

4.1. Force Analysis

The growing role of simulation in digital architecture has led to representations which appear similar to analysis in other industries: aerospace, automotive, manufacturing, medicine, meteorology, marine, etc. These industries have been using these tools far longer than the building enterprise to assess problems and search for efficient solutions prior to fabrication. This analytical process adds value during design development by the accurate analysis and optimization of product performance.

*Finite Element Analysis (FEA)* and other structural analysis tools are used to simulate and display stresses by color mapping or producing diagrams which graphically show deflection and deformation. Engineering firms such as Thornton-Tomaselli frequently deploy diagrams created by these methods to help them visualize structural optimization. In the case of the Soldier Field renovation/addition in Chicago, the enormous size of the project, in addition to a highly restricted deadline, dictated the use of digital analysis tools to simulate a variety of loading conditions including the collective vibration and sway of spectators during the course of sporting and concert events (Figures 3 and 4). Digital models facilitate the rigorous performance calculations for a range of loading conditions. A spin-off benefit is that structural steel or concrete digital models are useful downstream for the purposes of structural detailing, fabrication, and erection (see Figure 2).
Figure 2: Comparisons of the digital steel model and the completed Soldier Field (Images courtesy of Thornton-Tomasetti).

Figure 3: Example of a Finite Element Analysis (Images courtesy of Thornton-Tomasetti).
Computational Fluid Dynamics (CFD) is another effective way to predict performance completely within the digital environment. CFD tools simulate the flow of forces such as heat, forced air, wind, smoke, water, and other fluids. An interesting characteristic of analysis imagery is the common use of color maps of the visible color spectrum, red and blue/violet typically representing the two extremes of the forces being measured such as stress, velocity, or heat. While this graphic rule-of-thumb makes analysis diagrams easier to understand for the lay-person, especially a client who is interested in efficiency and life-cycle energy costs, it is not a substitute for the design, structural, or mechanical expertise needed to design and engineer a building. Rather, these tools augment the expert’s tool set to accurately analyze and “fine-tune” projects that are rich with complexity. Through visualization, design and performance information is fed back to the designer who may adjust the final form accordingly (hence the term we use frequently of “informed form”). This process/product approach and continual feedback through the digital exchange is paving the way for new performance-based rather than prescriptive design.
4.2. Production Analysis

Sectioning, unfolding, and nesting diagrams are all extracted from the digital master model as a means to directly generate the tooling and manufacturing of building components, and replace conventional fabrication shop drawings. While final fabrication commonly takes place at the end of design work, and data is prepared specifically for direct communication with CAM software and computer-driven machines, the quick automation of these new forms of representation by special algorithms allows design teams to create unfolding and nesting diagrams throughout the design process and test them with small-scale models. As the digital model is augmented, altered, and improved, the parametric fabrication files automatically update in real-time, giving the designer instantaneous feedback. The feedback loop from making prototypes, in turn, provides additional design consideration of efficient use of materials and machining time or testing variations of skin panel patterning. For example, the modularity of the Porter House curtain wall, by SHoP Architects, was determined by the most efficient way to nest unfolded panels within the standard size of zinc metal sheets. In this way, efficient modes of production, intended to minimize waste, can be built into the master model as each component is informed by its own fabrication criteria. Sheet metal sizes and operative conditions of fabrication inform the design as it is fed back into the design process as an input parameter. Additionally, fabricated mock-ups and prototypes can be manufactured in this way to test tolerances. Just as photographers perform bracketing tests to slightly adjust the parameters required for capturing the perfect image, the digital architecture team can quickly generate details to achieve perfect fitting tolerances for building components using bracketing of the operative parameters in fabrication.

Gaussian Curvature Analysis can be used to check the manufacturability of a surface by analyzing the surface quality and curvature magnitude. Commonly used terms such as “surface continuity” and “developable surfaces” refer to the operational unfolding/unrolling of surfaces into flat sheets for machining rather than spatial or tactile qualities. Clash detection, to check for interference or overlaps between different model components, now occurs entirely within the digital modeling environment, rather than by coordinating a series of two-dimensional ceiling plans and wall sections.

As a result of the modeling, which holds multiple layers of information about the production of the project, the nature of contract documents must change, as well. Consider the difference between the typical set of two-dimensional construction drawings and three-dimensional exploded assembly diagrams. Frank Gehry and Associates still use paper contract documents which only provide the typical pictorial representations without any dimensional information—all dimensions come from the digital model and the model is synched with the assemble via bar-code technology and laser positioning systems [13-15]. Different forms of contract documents are
necessary when each component’s shape and location within the entire assembly is unique. Already, the structural steel engineering, detailing, and fabrication process is quickly becoming a seamless stream of digital information rather than the paper-based documents of the past.

While typically occurring behind-the-scenes, the new representational tools of sectioning, unfolding, bracketing, curvature analysis, and clash detection allow the design team to make more informed and more efficient design decisions in less time and are necessary for communication between architect, engineer, and fabricator as the project is crafted and information feeds back into the design.

4.3. Complexity Management

While plans and sections were suitable for the production of buildings in the past, digital processes favor the emergence of multiple unexpected or unintended solutions. This does not render plans or sections unimportant, as they are still necessary to communicate spatial and organizational ideas in architecture, but new forms of representation are also necessary to understand the complexities of digitally derived architecture. Matrices allow for the quick visualization and prioritization of solutions in relation to each other, while also allowing one to trace a genetic history of design decisions, operations, or even projects. Matrices are helpful in that they visualize input parameters and actions with slight variations to assist in the selection of a direction for the design process. Foreign Office Architects’ phylogram is an excellent example of the matrix used to organize a series of projects by the operative procedures that generated them, resembling a genealogical tree [16].

Parametric relational structures, such as those generated in CATIA, Generative Components, and Pro Engineer, provide an important way for designers to move beyond visual representations to the issues and relationships underlying the operational and geometrical make-up of architecture. Related to this matrix is the relationship tree, which is a mapping of the rules, constraints, parent/child relationships, and parameters of a project. This relationship tree is continually adjusted as the project evolves by way of the feedback loop. This form of mapping operations allows the design team to manage complexity as projects usually exist as a multiplicity of files that elude the typical notions of one holistic identity [8].

The parametric relational structure is a way of organizing variations in the feedback loop-based digital processes, a way in which one perceives the richness of careful decision making by visualizing beyond the static representation of a design’s final form. As digital tools provide the opportunity for serial differentiation, countless design variants are generated during the design process. Matrices and relationship trees allow the designer to manage and examine this repetitive complexity; they are a graphic way to represent past decisions.
(good or bad) in the context of the resulting variants, as well as, to direct the next set of decisions and chart new courses of inquiry and exploration. They are also useful in arranging morphological variants created in surface/form-based searches and animation sequences, generated by key-framing, inverse kinematics, or scripting. For a good example of an effective use of these innovative representations in the process of design development, we turn to the matrices that Andrew Kudless used in designing and making the “Manifold Project” as part of the Architectural Association’s Emergent Technologies + Design Group (shown in Figure 5).

Here, the matrix kept track of the lineage of strategies and parameters used to produce a set of prototypes, utilizing a feedback loop, until the optimal combination was identified and the final path to resolution selected.

Figure 5: Manifold Project: Parametric matrix used throughout the project to explore the honeycomb system’s geometric and topological properties (Image courtesy of Andrew Kudless/materialsystems.org).

File management is an important emphasis in the digital exchange. Here a matrix or relationship tree is useful to understand the various operations and file structures. As noted above, components in the digital model might be defined in multiple files for the necessity of simulation and fabrication—for instance, a three-dimensional surface might also exist in a separate milling file as a flattened two-dimensional shape. Zahner Metals employed the use of a format operative flow matrix (Figure 6) to keep track of the flow of digital information for the fabrication of Herzog and de Meuron’s copper skin cladding of the de Young Museum in San Francisco. Digital model files were charted according to the operations performed (such as shearing, punching, perforating, and dimpling) and the timetable of the fabrication and assembly process. The ability to manage the digital information exchange between all parties was critical to the success of the project.

Figure 6: Operative flow matrix of all of the digital information and files for the detailing and fabrication of the copper skin panels of the de Young Museum in San Francisco (Image courtesy of A. Zahner Metals).
New forms of representations are emerging out of necessity due to the complexities of information flow and are becoming more commonplace in digital architecture. Our hope is that they will evolve with a rigor and scholarly attention. Our aim here is to suggest a few initial steps towards codification strategies for these representational matrices for design of digital fabrication projects in the future.

5. VISUALIZING THE FEEDBACK LOOP: CASES, BALL STATE UNIVERSITY

We tested some of the representation implications for digital fabrication during a semester long immersive seminar through the Virginia B. Ball Center for Creative Inquiry at Ball State University entitled: Streams: Data-driven Fabrications Connecting Indiana's White River. A series of installations were inspired by and drawn directly from the White River, which courses through the heart of East Central Indiana. The digitally fabricated projects were team-based collaborations: Calibration Chamber was created by digitally fabricating materials (Indiana Hardwood and Indiana Limestone) donated by local suppliers interested in the ideas of the digital exchange. A second project, C(+)DA: Parametric Boundary, was developed in collaboration with SHoP Architects in NYC and A. Zahner Metals in Kansas City—both organizations already fluent with the digital exchange.

In the C(+)DA project (Figure 7), located in Muncie, Indiana, the material (sheet steel) and fabrication operations were identified up front and a budget/labor/effect matrix was created as a way to understand iterative folded-paper form studies with regard to pragmatic criteria (Figure 8). The students quickly visualized the production and budget implications of every break, perforation, or shear operation. Broken folds began to articulate space, but also stiffen the three-dimensional, folded form. The perforation patterning originated from half-tone images of waves mapped to the surface of the metal, patterned for screening light and sight, as well as reducing the weight of cantilevered panels. In this way, the form carefully emerged from a feedback loop informed by program, site, structure, production, and resources. Matrices (Figures 9 and 10) were necessary to organize the process—one in which the solution became richer as constraints and parameters were added. Combined geometries delivered unique attributes, and the appropriate combinations that fit the defined site parameters decided favorable paired outcomes. It is important to note here that the process is not exhaustive, and the matrix can be re-entered at any point and altered for new criteria. Unfolding patterns and visual perforation patterns (Figures 11 and 12) were extracted from the digital model and scripts were written in Visual Basic to automate the file preparation for fabrication. The project was designed, fabricated, and installed in a mere five-week time period, which was only possible due to the quickened pace of the digital exchange (Figure 13).
Figure 7: C(+)DA: Perimetric Boundary.

Figure 8: Budget/effort/effect matrix for balancing budgetary constraints against formal decisions, C(+)DA project.

Figure 9: Folded prototype matrix organized by fold-plan and digital morphological variant matrix, C(+)DA project.
Figure 10: Matrix of the form generation from fold types (top) and favorable generations, C(+)/DA project.

Figure 11: Half-tone pattern generative diagram by tonal value of river wave images, C(+)/DA project.

Figure 12: Half-tone pattern, fabrication file of the same half-tone pattern (only the center points are needed), and final perforated panel, C(+)/DA project.

Figure 13: Design + fabrication from digital model to patina prototype, C(+)/DA project (photos by Christopher Peli).
In the Calibration Channel project at Mounds State Park (Figure 14), efficiency in nesting was the key determinate of fabrication organization, as only a limited amount of donated Indiana Hardwood was available. There were over 150 uniquely-shaped components to be CNC milled (Figure 15). Interestingly, once the three-dimensional model was completed, two-dimensional patterns were extracted for generating mostly simple 2-axis milling operations-drilling, pocketing, and shape contouring (Figure 16). The student team tried to limit the number of different milling operations with different milling bits, quickly recognizing machining time as an important constraint of production. The components were marked sequentially to eliminate the need for paper assembly instructions (Figure 17).

Additionally the master model was deployed and tested in prototyping the project’s limestone bases before the information was sent directly in model form for fabrication by local stone fabricators. The Indiana Limestone Fabricators (ILF) were surprised by the fluidity of the process from receiving the actual three-dimensional model (they were used to working with two-dimensional construction documents). As such, they are looking into requiring model files for all future building projects.
6. CONCLUSION

A new toolset of representational devices in architecture is necessary and will be useful to assist the designer in visualizing information that informs their digital design processes by informing form. While useful mostly behind-the-scenes in the case of digital fabrication, representations of the design, simulation, and fabrication processes are powerful tools for the design team to organize and manage complexity, streamline the design and...
fabrication process, and to test and simulate qualities of production. It should be noted that, while these representation tools seem cutting-edge to the profession of architecture, most of them are imported and adapted from other disciplines and industries. The increased need for the digital exchange between the many varied agents in the building enterprise raises larger questions of who is responsible for the collection, organization, visualization, dissemination, ownership, and responsibility of digital data. The notion of authorship (and for that matter, ownership) of the digital database/model is blurred. Visualization of the information streams is necessary to understand the potential of the information. These tools are extremely useful for architects in the development of a process/product [7] and will continue to evolve, and challenge the methods of future architectural practice. New kinds of devices and techniques for representing the digital fabrication feedback loop will assist in the evolution of these practices. If we proceed with rigor in the development of innovative techniques, we can chart a course that moves us in the direction of an architecture that is of our age.

Acknowledgements
The authors would like to acknowledge Christopher Peli, a Summer Research Fellow at Ball State’s Institute for Digital Fabrication, for his help with preparing some of the notes and images and providing feedback on the text describing the Calibration Channel and C(+)DA projects. Also, the authors would like to thank the Virginia Ball Center for Creative Inquiry and the Center for Media Design at Ball State University, as well as industry partners A. Zahner Co., SHoP Architects, Indiana Limestone Fabricators, Inc., Big Creek Limestone Quarry, the Indiana Hardwood Lumbermen’s Association, and Frank Miller Lumber Co. for their generous support of these projects.

References