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How are digital tools changing the process of architecture and building? From the perspective of a computer scientist, this discussion has a potentially surprising starting point: contrary to sculptors, for example, architects very rarely work out a design on site, on a one-to-one scale with their hands dirty from manipulating an actual building material. The clay in architectural design processes is usually replaced by immaterial means, starting with a pattern of neuronal activity in the designer’s brain (an idea) and then gradually being externalized, refined and materialized as spoken or written language, drawings, plans, scale models and so on. The result, at least ideally, is an unambiguous set of instructions for the builders, who then actually get their hands dirty in a separate phase of the process. In short, architectural design is a process of developing, describing and communicating ideas and of generating, transforming and exchanging information—over different media and between numerous involved parties.

Once we look at the design process from this point of view, it becomes clear as to why the current development in digital design and fabrication tools has fostered a great deal of expectations. Computers are tools to store and manipulate information, and their connection via the internet has formed the most powerful

Figure 1. Diagram showing the flow of information between the various software programs used for planning and fabricating the timber roof structure of the Centre Pompidou-Metz by Shigeru Ban and Jean de Gastines.
platform for information-interchange ever. The idea of integrating computer-aided methods from design (CAD) through engineering (CAE) to manufacturing (CAM) and seamlessly transporting the information from the designer’s idea to the materialized result is indeed captivating. In reality, however, it is still a huge challenge to form such a continuous “digital workflow”. Why is this so difficult?

THE LANGUAGE OF ARCHITECTURE

One very common complaint concerning the integration of digital workflows is the insufficient state of software and hardware technology and its multitude of incompatible standards. This is not at all restricted to architecture but seems to be a universal problem in all domains that try to map their analog processes into the digital realm. Why is it not possible to finally come up with one universal standard file-format for the building industry—one that can be used by architects, engineers, builders and all other involved parties to store knowledge about a building and the process of its realization in one integrated model, which then delivers unambiguous, consistent information to everyone in the project? [Figure 1]

In former, analog times, changes on one document had to be retraced in all associated documents of all other involved parties, which rarely ever worked and thus led to inconsistencies. Moreover, architects and engineers used different standards for drawing and describing things. And even within a single domain, one line on a plan or one number on a spreadsheet could have a multitude of different meanings, depending on interpretation. Like any other (natural) language, the language of architecture was ambiguous. But as those who read and understood this information were more or less successful at performing plausibility tests all the time—depending on their knowledge and experience—they were able to interpret the given data more or less adequately.

Computer languages, on the other hand, are unambiguous, formal languages. Anybody who ever tried to program a computer came to a point where a single missing semicolon somewhere in the code prevented the whole program from running, or even worse—led to unexpected and wrong results. What holds true for a computer program is equally valid for all data to be processed by a computer.1 In order for an algorithm to make sense of the given information, both have to be unambiguously encoded in a formal language, correct to the last semicolon. Therefore, a digital model of a building that has to be automatically processed by a computer program needs to be unambiguous in order to obtain correct results. An algorithm does not “guess” the correct interpretation of some data based on experience and intuition like a human expert would do. It interprets the information based solely on its built-in rules. Wherever it detects ambiguities or contradictions it stops with an error message. However, in order to be able to detect these uncertainties, programmers must have anticipated the problem and implemented the necessary checks within the program. Otherwise, as is often the case, the algorithm will not even note the problem and just carry on with some interpretation that is utterly incorrect.

In order to come up with a unified data format for all building purposes, including descriptions of shape, material and the building process itself, we would first have to develop a unified, formal, machine-readable language for unambiguously describing all these aspects of architecture. Although there has been an ongoing attempt since 1995 with the “Industry Foundation Classes” (IFC), an open standard for so-called “Building Information Modeling” (BIM), there have been long delays between releases of new versions.2 This timeframe between releases poses an interesting dilemma: while new versions of software packages with new functionality appear on the market every year, a four-year innovation cycle for the underlying data format seems rather unhurried. Can the IFC standard keep up with the development?

STANDARD VS. NON-STANDARD

Standards are defined to make life easier. They ensure that different CAD programs read the same information from the same data and that the quality of service is comparable among bidders in a tender. But standards do not only make life easier, they also make life simpler. Standards reduce the infinite possibilities of the real world to the least common denominator of all involved parties. In the case of the IFC, for example, a building cannot have any curved free-form shapes. They simply cannot be described within an IFC model, because the definition of such shapes is not (yet) part of the IFC standard. A precise mathematical theory of those shapes (called NURBS3) has been available since the 1950’s, and many of today’s CAD packages provide the necessary functionality to model them. But obviously, when IFC2x3 was defined and approved only a few years ago, the
precise modeling of curved shapes was regarded as low priority compared to other features. When you look at architecture magazines today, you might think that that was a downright wrong decision by the developing association IAI.

On the other hand, putting the curved buildings that made it to the pages of the architecture magazines in relation to the total volume of buildings erected during the last four years, the decision seems more reasonable. Why inflate a nice and lean standard with a feature that is needed for less than one percent of all buildings in the world? All AEC software would have to correctly interpret the NURBS definition just in order to be compliant to the IFC standard, regardless of the fact that in hardly any project this feature will ever be used. What a waste of software engineering resources! Since most of the IAI members are software vendors and draw their decisions on the basis of economic considerations, they consequently decided not to waste scarce resources to address less than one percent of the building industry. Apart from that, even the least-standard buildings contain a lot of standard nuts and bolts. And although the next version, IFC2x4, will contain NURBS there will always be non-standard objects that can be neither described in standard terms (or languages or file-formats) nor built with standard tools.

from standard materials. No matter how many new functionalities are added, a standard tool will always only work for standard designs. And creative designers will always try to escape or overcome the standard. So, how do we deal with non-standard architecture?

UNIVERSAL MACHINES

Where no standard solution for a problem is readily available, a custom solution has to be found. And here is the real advantage of digital tools: they are "universal machines". The functionality of a computer is not inscribed in its hardware but is defined by the software loaded into its memory. If the needed function is not available in one version of the software, an extended version can be programmed and run on the same hardware without changing the computer. This functionality has become so common in design practice that it does not make us think anymore. But going one step further into fabrication, the same principle still applies— and often surprises designers who have been educated to use industrialized, mass-produced components: a computer-controlled (CNC) fabrication machine does not care whether it is producing a thousand similar or a thousand different work-pieces. If the needed components are not readily available, a CNC tool can

Figure 2. CNC milling allows fabrication of complex non-standard components that can fit together into an intricate structural assembly.
custom-produce them for almost the same price as industrial standard components, while the machine itself stays unchanged. [Figure 2]

These developments have changed the prospects of non-standard architecture quite drastically. When standard software can be extended to precisely fit the needs of the designer, and individual components can be custom-made instead of arraying standard-ized, industrially fabricated pieces, then a new world of possibilities opens up. Yet at the same time, any ad-hoc extension of a standard tool will lead to incompatibilities in the workflow. If something outside the IFC standard is modeled in a CAD software by means of a custom extension, the extended information can no longer be passed on to an IFC-compatible standard CAM software. The chain of information breaks and to close the communication link again, both the exchange format and all dependent tools have to be extended appropriately. And besides data exchange, other challenges arise.

Figures 3a (bottom), 3b (top). Planar glass panels on the façade of Renzo Piano’s Peek & Cloppenburg department store in Cologne.
LOGICS OF MASS CUSTOMIZATION

Architecture’s departure from repetitive, industrialized, orthogonal designs can quickly become a labor-intensive nightmare. For example, when façade panels are to be curved, new workflows have to be developed, because standard building materials come in either straight sticks or flat sheets. To avoid the problems of bending, curved shapes can be approximated with small planar facets, but that requires meticulous optimization of the panel sizes in order to achieve both visually appealing and economically balanced results. And no matter whether the components are curved or straight, every component and every joint has a slightly different geometry due to their non-regular shape. The convenient set of standard detail drawings is replaced by hundreds and thousands of individual workshop drawings or thousands of individual programs for a CNC machine. [Figures 3a, 3b]

Today, drawing can be automated. Many CAD systems can take the defining properties of a component or joint as input and deliver a perfect drawing (or model) as output. Instead of drawing a line by pointing and clicking with the mouse, the user writes a custom program, or “script”, that generates the line in the model based on a set of rules and parameters. Some CAD systems even allow the construction of such “parametric models” by graphically connecting “algorithm building blocks” without writing a single line of program code. Hence, the functionality of standard CAD software can be extended with custom tools to allow innovative and curious professionals, who lack a degree in software engineering, to build their own digital tools. The designer becomes a toolmaker. But no matter how such a parametric model is built, it adds another layer of abstraction to the modeling problem. Instead of producing a description of an object by building a digital model, first a program has to be written, which then generates the description of the object. Obviously, this additional effort only pays off when something more complex than a line has to be drawn more often than just once. If the same script could generate drawings for all the different joints of a non-standard façade, it would make sense to invest a couple of weeks into programming.

This requires that instead of finding one well-formed, unambiguous description for one single component, a common abstract description has to be found that satisfies the needs of all individual components. And in order to eventually materialize the components, a complete production chain has to be implemented, including planning, material procurement, (digital) fabrication, quality management, logistics and assembly of individual one-off components.

In the consumer goods industry this is known as “mass customization”. The client defines the measurements of his new shirt or the configuration of her new car, and some days or weeks later the product arrives, custom-built to the given specifications. In architecture, mass customization is often associated with prefabricated houses. Economists would call...
that a business-to-consumer (B2C) model, and it requires finding a sufficient number of clients, each one paying for one “customized” house, in order to remunerate the initial investment of the fabricator. However, with large architectural projects mass customization also works on a business-to-business (B2B) model. The façade of an office building, a museum or a concert house easily comprises many thousand components, and they may all be ordered by just one client. Implementing an integrated planning and production process for those components can easily pay off within a single project. A project-specific standard is created: a complete mass-customization solution, starting with a digital planning tool that parametrically defines the shapes of all necessary components and resulting in digitally fabricated parts delivered to the construction site. After the project is finished the whole process usually gets discarded, because no designer would want to build the same idea twice. Apart from that, large projects usually go on for a couple of months or even years and involve many people from diverse disciplines. For future projects the team members and the available technology will likely be different, requiring a new process.

SYSTEMATICS AND COMPLEXITY

It has become clear that a parametric approach has its biggest advantage where complex solutions are achieved by simple systems. A successful parametric model is as simple as possible, while still covering the extreme cases. When the tightest curved panels and the most skewed joints define the parameter range of the solution, all other cases can be easily addressed and the whole façade or roof can be constructed from only a few types of parametric components. This approach to simplicity is too often confused with solving the simple cases first and then adding a few special cases wherever the simple solution fails. On orthogonal standard buildings, this works reasonably well, but on non-standard buildings with complex shapes, things are different.

Complexity can be defined as a measure for the amount of interdependencies in a system. When complex systems are not designed with great care, the high level of interdependencies is liable to lead to a solution tree that branches to the point where all cases are special and every single one has to be solved individually. By Kolmogorov’s definition, this is the most complex state possible: 100% exceptions, with every single case described separately. In order to reduce this complexity and design, a good parametric system, a common rule on the basis of all those special cases has to be found. This can then be encoded in a lean parametric model, and by changing the parameter values a couple of thousand customized data sets for automatically fabricating individual components are easily generated.

But if the changes result in violating the parametric border conditions of just one single component—maybe a glass panel of a façade gets a notch too big to be cut from a standard size—the whole system stops working. Either the façade has to be changed again until all parameters are within their range, or a special case has to be introduced to the system to solve this exception.

Unfortunately, all this is not a question of buying the right software tool. Computers are good at storing information and crunching numbers, but it takes human thinking to find a good solution and describe it concisely. It takes a team of specialists knowledgeable of all stages of the planning and fabrication process, who define a common model just complex enough to describe the solution.

Figure 5. All 4,000 joints in the timber roof structure of the Centre Pompidou-Metz have a different geometry, but they follow the same simple rules.
MINIMAL MODELS

The purpose of a model is to condense the complexity of the real world down to a level where certain things can be communicated or simulated without having to build the real thing first. Contrary to current belief, a perfect model does not contain as much information as possible, but as little as necessary. The art of modeling is based on the ability to sort out, to leave out everything that is not relevant for the given purpose, while including everything that makes a difference. The quality of a model is therefore closely related to its purpose. What might be a good model for a structural engineer, because it contains a structural wall panel that spans continuously from the ground to the top floor, is likely to be less useful for an interior designer, who needs to get the inner wall areas between floor and ceiling painted in every story. To make the same model useful for both parties, either the same wall has to be described twice—which adds redundant information and leads to inconsistency—or rules have to be defined that translate the engineer’s definition of the wall into the definition needed by the interior designer—which adds complexity to the interpretation algorithms. Multiplied across an entire building, these increased definitions for single components inescapably lead to models that are “fatter” than necessary for either purpose. And when we naively continue to integrate all necessary information for all involved parties from design to facility management, our models will quickly become clumsy, slow and not useful for anyone. This is why on reasonably large architectural projects, there will always be a multitude of models serving a multitude of different needs.

If a model is to be used as the input for computer-controlled fabrication equipment, it has to be very precise. Even large-scale CNC tools are able to work within tolerances smaller than a millimeter, allowing the prefabrication of half a millimeter. A tolerance gap of only 2mm between the modules was sufficient to hoist the elements into place.

Figure 6. Each of the 32 roof modules for the Heasley Nine Bridges Golf Resort in South Korea, designed by Shigeru Ban, has a footprint of 81sqm. It is assembled from some 150 individual timber components, CNC-cut-to-fit within
meter-long components that click into place like Lego bricks. [Figure 6]

But lacking any sense of quality, the machine also reproduces flawed input data with the same unforgiving precision—if there is a kink in the CAD model, there will be a kink in the final product. Taking into account the numerical errors occurring during the modeling and calculation processes, the precision of the model has to be even a degree higher than that required for fabrication. Usually the CAD models produced in architectural or engineering offices do not even come close to these requirements, because their purpose is to generate renderings or drawings. Only when it comes to fabrication, does the description of geometry have to be absolutely precise and contain every single bolt hole that has to be pre-drilled before the components are shipped to site. To precisely position those details the mathematics, so comfortably hidden behind the CAD software's buttons, suddenly have to be dealt with in the form of normal vectors, curvature measures and coordinate transformations—a field of expertise that is often tolerantly skipped during the education of architects and engineers. What initially could have been described in a sleek, elegant mathematical formula now has to be dealt with in the form of a clumsy point cloud and long tables of coordinates, because somewhere along the process a lot of fix points were defined just a tiny little bit off the mathematical surface—what was easier to model early in the process results in difficulties later down the line.

To produce a roof the size of the Centre Pompidou-Metz, a CNC machine of a size that needs its own factory hall runs for six months, twenty-four hours, seven days a week. Neither the raw material, which has to be custom-made and ordered weeks in advance, nor the finished components can be stored in one place, so both procurement and production have to run just-in-time synchronized with the assembly schedule. Fabrication and building sites are far apart, so the components have to be transported and need to fit onto standard trucks and containers, which adds dimensional and weight constraints as well as a few extra joints on large pieces. All connections have to be precisely positioned and joined on site, which sounds much easier than it is on a curved puzzle with 2000 pieces, each the length of a bus. It would be unrealistic to expect all this being already defined in an architectural model. The knowledge that needs to be embedded in this process is distributed over at least half a dozen domains. In order to integrate this know-how, they all have to work together, understand each other's needs and sort out all interdependencies. And as the project is non-standard, there is no standard procedure to follow.

This is the main difference to industrialized production: mass production is based on standardized processes with standardized interfaces. The input and output of every process step is clearly defined. As long as the interfaces between them stay unchanged, every section of the process can be optimized locally and individually without considering the other sections. In other words: all the specialists can comfortably stay within their domain, their borders clearly defined by agreed standards.

**CRAFTSMANSHIP**

Setting up the process for a non-standard project means first and foremost defining those interfaces. All the interdependencies have to be untangled carefully while constantly being concerned about both the final result and an efficient process to get there. Again, this needs experience and expert knowledge, deeply rooted in practice. But even more, it needs the ability to look beyond one's own domain, to consider the consequences of every decision and—since the necessary know-how will not be embedded in the brain of one single expert—the willingness to team up and collaborate. It needs a group of specialists each being extremely experienced in his/her field, open enough to discuss with others and committed to quality. In short, it needs craftsmanship, as defined by Richard Sennett: a sort of craftsmanship that is not identified by the fact of actually getting one's hands dirty in a workshop, but by intrinsic motivation—an "enduring, basic human impulse, the desire to do a job well for its own sake", a combination of "material consciousness" with the experience of years of practice, a strategic acceptance of pragmatic ambiguity, rather than an obsessive perfectionism, and a never ebbing desire to learn. In this context, modeling experts, computer program-
mers, engineers and architects can all be good craftsmen. Their skills are never going to be replaced, but can be dramatically enhanced by digital tools.

ENDNOTES

1. Computers following the so-called “Von Neumann Architecture”—and that means almost all contemporary computers—do not even differentiate between program code and data and store both in the same memory.
2. IFC was developed by an association of firms named the “International Alliance for Interoperability” (IAI). Many software packages for the building sector are already able to read and write IFC data and by many the IFC are seen as the future of digital workflows in building. Currently, IFC2x3 as of February 2006 is the latest approved version, a release candidate for the next version IFC2x4 was presented in May 2010. Detailed information on the IFC can be found online at the IAI website at www.buildingsmart.com. For an overview on BIM, see Eastman, C.; Teicholz, P.; Sacks, R.; Liston, K. (2008) BIM Handbook, New Jersey, John Wiley & Sons.
3. Non-Uniform Rational B-Spline Surfaces (NURBS), as a mathematical theory to precisely define curved surfaces, were developed in the French car industry in the 1950’s.
4. It might be able to pass on the data, but the CAM software has no valid interpretation rules to make any sense of it.
5. E.g. “GenerativeComponents” for Bentley’s Microstation or the “Grasshopper” plugin for McNeel’s Rhinoceros software.
6. In algorithmic information theory, the Kolmogorov Complexity of an object is defined by the shortest description of the object in a given language.
7. Due to the encoding of real numbers into strings of zeros and ones, computers make tiny rounding errors in every calculation. Apart from that, many geometrical operations cannot deliver mathematically precise results but only approximations in order to keep processing time within reasonable bounds. If those errors add up the result can be completely flawed—which for example is a common reason for failing operations in Boolean geometry.

CENTRE POMPIDOU-METZ

WORKFLOW CASE STUDY

Shigeru Ban, Jean de Gastines and Philip Gumuchdjian won an international competition to create an extension to the landmark Centre Pompidou in Paris. Their design for the new building, located in the eastern French city of Metz, included several suspended, rectilinear galler-ies under a curved roof that was inspired by a Chinese hat made of woven straws. As the project developed, these straws evolved into 18,000m of timber beams with a cross-section of 14 x 44cm to form the roof structure. These beams had to be individually CNC-fabricated, with intricately designed joints to maintain the design intent, preserve the structural integrity and allow efficient on-site assembly. As part of the construction team, designtoproduction created reference geometry for the roof and provided the timber construction company with the necessary CAD-tools to efficiently define, detail and produce nearly 1,800 double-curved wooden glu-lam segments.
Workflow 1. The mesh for the roof structure of the Centre Pompidou-Metz as originally provided by the architects was more free-form in design and could not be built in an economic manner. Design to production helped rationalize the form into a triangulated mesh, based on a system of rules that could be calculated and constructed. A wireframe model was developed from this refined geometry.
Workflow 2. From the wireframe, a structure could be designed that would conform to the underlying geometry. In this case, wooden glu-lams were used to create the complex, curving structure.
Workflow 3 (top left). Because no two connections were the same, specific joinery had to be created at each intersection, resulting in a complex schedule of assembly details.

Workflow 4 (top right). It was important that the material properties of the wood, such as how it would behave when cut at a certain angle, be programmed into the system early on in the process, so that the wireframe could parametrically adapt to these rules.

Workflow 5 (bottom). design-to-production was able to provide the timber fabrication company with the necessary files to define and detail all 1,800 double-curved wooden glu-lam segments. Each curved timber piece was first made up into the approximate geometry, indicated by the outlined shaded surfaces. The precise geometry used to mill the finished member is shown by the inner solid surface.
Workflow 6 (top left). CNC machining tools would mill the final precise geometry derived from the model. The machines could perform quickly and operate on each piece of structure at the same rate, regardless of differences in design.

Workflow 7 (bottom left). Each piece was coded to fit together on site like a kit-of-parts. The plugs at the connection points allowed precise alignment for site assembly.

Workflow 8 (above middle). Roof structure being assembled on site.

Workflow 9 (above right). Completed project.
Working in close collaboration with the architect, engineer and timber specialists, designtoproduction developed a fabrication and assembly concept for the curved wooden façade of the Kilden Performing Arts Centre in Kristiansand. The workflow consisted of refining the design geometry from the architect in response to fabrication and assembly logics and then developing a parametric 3D model. The model contained data for 14,309 glue-laminated girders and locally sourced oak cladding that were then output from this model and delivered to the timber fabricator for CNC fabrication. This was one of several timber projects realized through a refined workflow, where the structural engineering of complex timber structures, provided by SJB Kempter Fitze, and the craft and digital timber fabrication skills of Lehmann Timber Construction were integrated through the parametric modeling of designtoproduction.

Workflow 1 (top). The initial model provided by the architects for the Kilden Performing Arts Centre seemed to be a simple ruled surface. However, varying undulations in the surface created unresolved geometry that was impossible to detail, fabricate and construct.

- 2 straight primary beams
- mounted to steel girders
- 18 seat cuts on inner face for secondary beams
- 8 seat cuts on outer face for assembly cradle
- 18 single-curved secondary beam segments
- 495 seat cuts for cladding boards
- 110 individually cut oak cladding boards

KILDEN PERFORMING ARTS CENTRE
WORKFLOW CASE STUDY

KILDEN PERFORMING ARTS CENTRE
WORKFLOW CASE STUDY
Developing the model parametrically allowed the designers to push and pull certain areas of the façade and get updates on the constructability of the system in real time.

Workflow 2 (facing page, left). Design to production rationalized the surface so that it used similar-sized planks and reduced the gaps and pinching of the original mesh.

Workflow 3 (facing page, right). The design goal was to create an underlayment system of ribs onto which the finished oak cladding boards would be fixed. The model included “seat cuts” that were CNC milled into the underlying ribs to make installation both easier and faster.

Workflow 4 (bottom, 5 (top). Developing the model parametrically allowed the designers to push and pull certain areas of the façade and get updates on the constructability of the system in real time.
Workflow 6 (above left). The parametric model contained information to CNC fabricate 14,309 glu-lam members and finished oak boards. Assembly logics were embedded in the joint details of each individual member.

Workflow 7 (above right). The substructure of glu-lam beams were secured to primary steel girders. The glu-lams were CNC-milled to accommodate these beams.
Workflow 8 (above left). The curved wood surface not only creates a dramatic façade at the waterfront but also provides beneficial acoustic properties to the theater inside.

Workflow 9 (right). By working directly with the fabricators and the architects, design-to-production was able to straddle the line between design concept and buildable solution, simultaneously reducing complexity and increasing efficiency.
One of the natural assumptions about Building Information Modeling is that the ultimate BIM model contains as much information as possible. Information gaps, which are a by-product of trying to describe a complex 3D object with 2D drawings, are supposedly eliminated by a comprehensive virtual model, creating an expectation that the design will be built exactly as planned. This assumption is partially a consequence of the AEC industry continually referencing the design and production workflows in the aerospace and automobile industry as a model, where detailed modeling of each part and high-level geometry resolution between all systems is a requirement for design and manufacturing. This comparison has played an important role in highlighting workflow inefficiencies in the AEC industry. Versions of highly integrated workflows have been explored on some of the more ambitious architectural projects in recent years. It is likely, however, that a more flexible model is needed for the particular conditions that define the difference between the two industries. Aerospace contracts are almost always design-built, which establishes standards and an industry-wide alignment of motivations and incentives that differ greatly from the AEC industry. Additionally, the one-off design of most buildings makes it a very different procedural problem from the mass production of a jet or car, where the time and effort required to create a comprehensive digital model can be justified through its repeated use.

The approach proposed by Fabian Scheurer is based on multiple minimal models—the art of good modeling where one is able to include as little information as possible to accomplish the goal at hand. This approach is especially relevant for the work of design-to-production, as they specialize in solving highly specific, information-intensive problems related to fabrication, assembly and construction execution. As Scheurer notes, manufacturing tasks usually require digital modeling at higher levels of resolution and tolerance than design tasks. Minimal models address this difference but raise the question of how to maintain continuity of design information from one minimal model to another without rebuilding anew each time. This will require another evolution of digital workflows, where the base design geometry of a building will be created as a wireframe that functions as a digital armature capable of receiving additional information as it develops during the design process or as it is needed during the manufacturing and construction process.

design-to-production is a workflow consultant. They produce targeted workflows between the formal innovations of architects and the manufacturing potential of CNC technology, filling some of those gaps in the design-to-production process. They are not experts in manufacturing, or the processes of construction, but through careful collaboration with experienced fabricators who have an intimate understanding of materials, and builders who know the logistics of site conditions, they are able to transfer this knowledge into code that manages the relationship between design geometry, material characteristics and assembly parameters. For the Centre Pompidou-Metz, for instance, they worked closely with Holzbau Amann, an established timber construction company in Germany with decades of experience in structural timber projects. By combining design-to-production’s programming skills with their knowledge of craft, Holzbau Amann were able to extend their conventional manufacturing capabilities to produce the double-curved glu-lam members that define the roof structure.

Much has been written about how the direct link between design and production through digital fabrication brings the engagement with materiality, detail and craft back into focus for architects. However, this is a very different type of engagement compared to modern times. Detailing is no longer defined by the negotiation of tolerances between pre-manufactured building components but rather, by the design of customized assembly logics with embedded material intelligence. Design-to-production workflows communicate that intelligence and drive the manufacturing process. This is what design-to-production does. Positioned between the detailing done by architects and the means and methods of contractors, they are typically hired by building contractors to solve logistical issues.
related to fabrication but arguably, they serve architects even more so by preserving the integrity of their designs.

This raises the question of when and where the renewed focus on materiality, detail and craft is really occurring. The future promise of encoding the knowledge of craft into algorithms lies in these algorithms being available to architects in the early stages of design. The time and effort to post-rationalize geometry could be repositioned to become part of its formation process. Production workflows could parallel design workflows.

1. Integrated Project Delivery (IPD) is the AEC industry’s current response to the potential of this business model, and while it addresses many of the legal obstacles to integrated workflows, it remains to be seen how it will impact design innovation.

2. See Neil Denari’s discussion of precision in “Precise Form for an Imprecise World” in this volume.