Parametric BIM as a Generative Design Tool

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INTRODUCTION

The promising directions in current design practice and teaching relate to creativity with digital tools in the context of building information modeling (BIM), performance analysis, and simulations as well as digital materiality (computational simulations of materials) and dynamics-based behavior. This line of research combines spatial design with building and material technology in search of effective and efficient architecture. It reconstitutes questions of what to design by interrelating them with questions of how and why to design. My research and teaching are closely aligned with this line of thinking and look into an integration of conceptual design with construction technology teaching.

Digital tools provide a unique capability to speculate creatively and simulate physically within a single design framework. Creativity is seen as both an abstract proposition and an actual implementation with a problem-solving value. Simulation and analysis tools allow for contextualizing design with real-life physical and construction considerations. While often criticized for its overemphasis on formal expressions and its pursuit of the spectacular, digital creativity begins to account for a multiplicity of design factors that define architecture. These factors relate to performance simulation and analysis, fabrication, and BIM. Usually associated with the back end of the design process (implementation), BIM could also redefine the way design ideas are generated by bridging formal creativity with design and technological innovation. This is achieved through a close integration of generative tools with parametric capabilities, through the introduction of digital materiality with physical behavior, and through intelligent database-enriched digital objects.

Introduction of performance-based design, with its quantitative and qualitative considerations, in the early design stages is particularly critical in the context of sustainable design. If, indeed, we want to have buildings that are defined by their performance and respond to aspirations such as zero-energy architecture, we need to include these parameters as form-makers during initial design stages.

Because of their CAD legacy, BIM-based tools lack significant generative design modules with fully operational bidirectional data connectivity and thus become peripheral within the creative process. Furthermore, BIM lacks specificity in programming and planning areas that could be effectively used in the predesign phases of a project. Additionally, the user interface does not adapt to various design tasks or software competency levels that would require an intuitive interface. It often feels too technical for senior (seasoned) designers who are occasional and casual users. At the same time, general-use, generative design software lacks the database dimension and material-based knowledge associated with its digital models. It often provides an ease of use and quick tool adoption, but it does not grow with the user's increased capabilities. Furthermore, although architects may be able to develop interesting designs, it is impossible to verify whether these designs correspond to anything physically constructible, nor can they be associated with a particular scale or with particular material characteristics. These designs often exist purely as visual propositions with no ability to advance into physical realization.

This discontinuity in the creative process between generative and implementive design stages exemplifies a significant limitation of digital tools.[1]

To bridge this gap, this paper investigates generative qualities of the BIM platform through a relatively narrow but potent set of examples of parametrically controlled constructional details and physically accurate material simulations. It proposes extending BIM interoperability and parametric qualities into early, generative design phases, thus introducing two-directionality to a traditional process that follows a general-to-specific way of conceptualizing.

DESIGN OPPORTUNITIES

This paper focuses on the appropriation of BIM tools for architectural curriculum teaching, from the design studio to building technology courses. It specifically focuses on BIM-based parametric modeling in discussing construction details, assemblies, and design explorations in the design studio context.

The introduction of parametric thinking into building technology and design courses promotes qualitative and analytic thinking in lieu of the descriptive or metaphorical. Transcoding conceptual design into highly interdependent and parametric sets of relationships confronts us with the need to understand design in a comprehensive way. While there is still a space for the imaginary, unknown, and unspoken, these are often predetermined by initial design assumptions in discrete ways defined by performance expectations. This not only allows for understanding the interdependencies between various elements of a building assembly, but also opens doors for "What if...?" speculative exploration. This second aspect of parametric thinking encourages students to bridge technical knowledge with creativity. These new creative factors reflect technical, functional, programmatic, or code knowledge as necessary competencies feeding into the design process.

With bidirectionally interacting parameters and dependencies, the cause-and-effect sequences can be reversed and tested for new possibilities. The initial design criteria (ideas) can be defined in the context of the ultimate design goals and performance values. Design becomes a logical, cause-and-effect sequence that can be executed in both didactic (general to specific) and inductive (specific to general) ways.

Parametric definitions of architectural components become fluid modifiers that facilitate exploring designs and testing design assumptions against established validation criteria. BIM in conjunction with physically based parametric design allows for the alternative design process that parallels traditional creating/making processes.

These new tools create opportunities to expand the conventional design process characterized by the hierarchical (didactic) thinking that starts with the general and gradually progresses towards the specific. With the parametrically defined BIM, broadened by physically behaving components and materials, there is an opportunity to establish the interoperability of data, or a bidirectional design process with designers simultaneously working on the general and the specific, within all phases and scales of the project. This would allow for the specific—a detail, assembly, or material—to shape the design outcomes. This inductive design thinking is already indirectly present in designs of Antonio Gaudi and Frei Otto in what we call today form-finding or form-making.

The following student projects extend these precedents of form-making by kinetic and adaptive designs as well as material and physics-based simulations.

CLASS METHODOLOGY

All projects discussed here follow a design methodology that starts with a construction component or material properties and pursues designs that naturally emerge out of the assembly of initial components. While this is an established approach[2], this study broadens this method by considering a broader set of design solutions resulting from parametric alterations and alternations of original components. It discusses the use of simulations as self-normalizing design validators that in some instances allow these components to exemplify their intrinsic constructional logic, as is the case with physically behaving materials and assembled components.

The final design project emerges through a series of explorations with fragments informing the entirety of the architectural design solution: fragments that are representative of the overall design.

To facilitate the effective learning in the context of digital tools, the course focused on selected BIM and parametric software capabilities that allow for open creativity with flexible design language. Defining appropriate architectural precedents became critical. Students were given contemporary designs representing high quality practices, which naturally translated into parametric and BIM platforms. Projects by Nicholas Grimshaw, Norman Foster, and Santiago Calatrava were just a few of the designs that fit well into the class methodology and were relatively easy to handle using digital tools. In each case, structural system and expression were clearly delineated with visually interesting and structurally accurate logic.

Waterloo Station, by Nicholas Grimshaw, was given as such an example, with trusses naturally morphing their shapes and thus responding to the overall design of the station [fig.1]. Such designed trusses, while each of them can be different, all follow the same parametric logic and could allow for design efficiencies associated with modular or adaptive components. This diversity of designs achieved through parametric variations of a single adaptive component could allow for new ways of integrating structures with architecture.

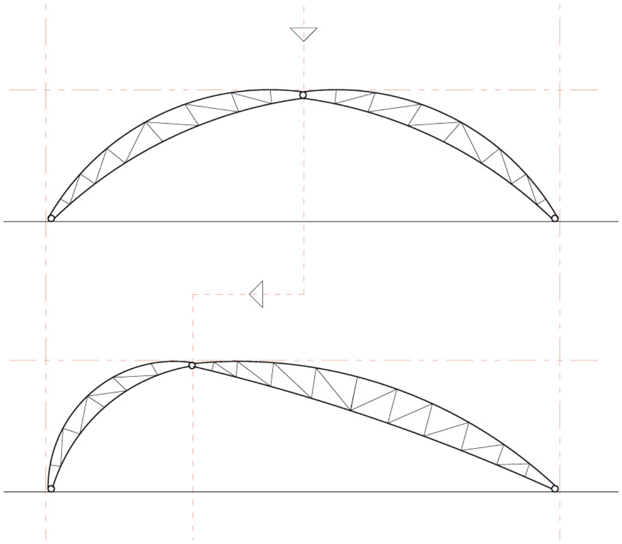


Figure 1. Waterloo Station, an example of parametric variations of a truss system. While these two assemblies look different, they can be seen as two parametric variations of a single design.

All chosen buildings had well-integrated and architecturally expressive structural components. The components performed clearly defined functions with multiple variations present in a building that allowed for relating them parametrically with one another. After selecting projects and particular assembly components or construction details, students were asked to study these precedents, model partial assemblies, and test them as a three-dimensional BIM models.

CASE STUDY: CONSTRUCTION DETAIL

This assignment had two distinct phases. The first portion of the assignment—knowledge building—focused on research and modeling of an architecturally significant precedent. Through the modeling students became familiar with construction detail, assembly, and the interface between architectural and structural systems.

The second phase—design formation—used the intrinsic ability of a parametric object (detail) to develop design scenarios that allowed for new design concept formation by transcending precedent into qualitatively new designs.

When choosing examples for their explorations, students were asked to consider the open-endedness of their particular designs and their ability to develop meaningful variations.

In this phase of the assignment, students learned about the spatial organization of various members and system components, their interconnectivity and interdependencies. Studetns were able to relate separate structural members into a single assembly and define construction details as a series of imbedded parametric relationships that interoperate on numeric values. These imbedded parametric relationships allowed for scaling up designs from smaller and simpler assemblies to larger and more complex

Figure 2. Parametric variations of the roof/skylight assembly (BIM model).

ones. These parametric hierarchies, discussed earlier, facilitate inductive design thinking with individual components informing an overall design.

Students also focused on identifying intrinsic flexibilities associated with particular designs and attempted to define them. They were able to manipulate parametric components and to explore interactively design variations [fig.2].

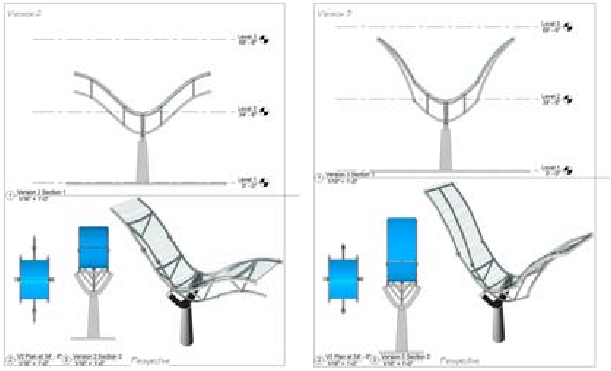


Figure 3. Parametric details allow for alternative design explorations and creating larger assemblies.

In the second part of the project, students explored the generative possibilities of parametric BIM models [fig.3]. Three-dimensional, parametrically resolved architectural details served as speculative, idea-generating devices for design. Students were expected to demonstrate the creative possibilities of their BIM models and to document their parametric explorations through images, digital models, and a text narrative (final report) [fig.4]

Figure 4. Parametric BIM models mimic adaptable structural components.

Another design strategy for the realization of flexible structural systems used an idea of a surface-based patterns as design generators for space frame design. This approach looked at the adaptability of individual space frame modules as defined by underlying surface geometry in figure 5B and compared to figure 5C. In this particular exercise, students did not test the structural performance of a system but rather focused on ways to define a design system that could allow for maximum flexibility and ultimately would lead to generating qualitatively new designs. A primary visual reference

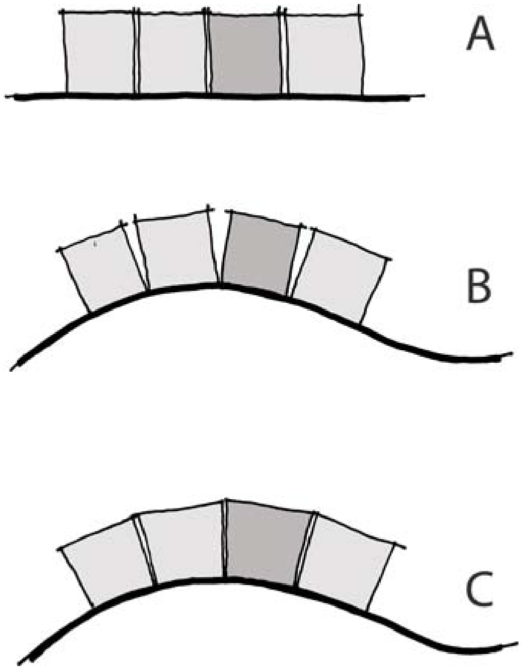


Figure 5. Three-dimensional geometry (modules) adapts to underlying surface. A square becomes a trapezoid.

for this group of projects was the Centre Pompidou Metz, designed by Shigeru Ban and Jean de Gastines, where a roof surface, a wooden lattice, naturally adapts from being a roof into elements such as columns. [[fig.6][3] Such a system uses construction components in a similar way as the parametric definitions discussed earlier. However, the focus is not on a parametric change but on the adaptation of an assembly to a new function it plays while preserving its integral character.

Figure 6. Centre Pompidou Metz with a roof surface as a wooden lattice adapting into a column.

The aim of this exercise was to help students to develop the technical knowledge necessary for the pre-comprehensive and comprehensive studios. Specifically, it addressed the integration of building systems and their appropriateness to the design intent. Additionally, this assignment facilitated material, dimensional, and construction detail investigations in the context of contemporary architectural practice. The level of the applied constructional knowledge for this assignment matched that of the comprehensive studio work and of professional architectural practice. Furthermore, students were exposed to an alternative way of designing, with technical knowledge and a constructability-based idea, not an abstract concept, as the design generator.

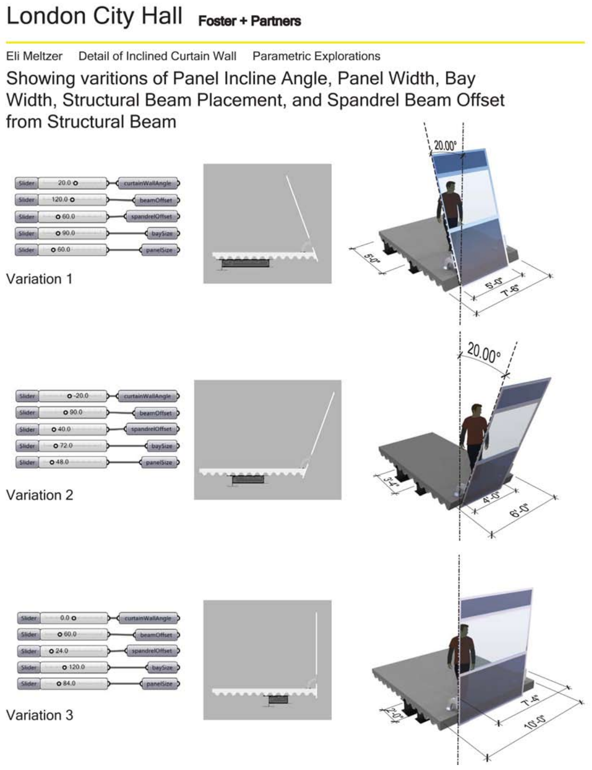


Figure 7. Digital construction detail with parametric relationships achieved with visual scripting (Grasshopper).

ALTERNATIVE APPROACHES

A number of students used other, non-BIM, parametric software, such as Grasshopper, to work on the construction detail projects [fig.7]. Initially they were able to develop geometries with greater sculptural definition and with a broader range of shapes as compared to conventional BIM software, such as Revit or Vectorworks. However, their scripts became increasingly complex, which often led to reduced flexibility in design explorations as well as increasingly time demending to maintain an ever-expanding definition. [fig.8] They often traded the design flexibility existing on the subcomponent level for the clarity and navigational ability of the overall design. While this approach gave students direct access to all the components with the ability to fully customize all interopperabiliites, these projects quickly became complex and difficult to scale up. Furthermore, the increased complexity of Grasshopper scripts made it difficult to pass the project to other collaborating students or revisit projects after a long period of not working on them.

However, in the long run, visual parametric environments such as those used in Grasshopper for Rhino allow more for the development of customer/user-driven features as compared with conventional, out-of-the-box BIM software. A number of third-party plug-ins and components are presently available. One of them, Kangaroo, is a physics engine with components that account for the simulation of a number of forces and material properties. This open SDK-like (software development kit) environment allows for dynamic development of the BIM platform.

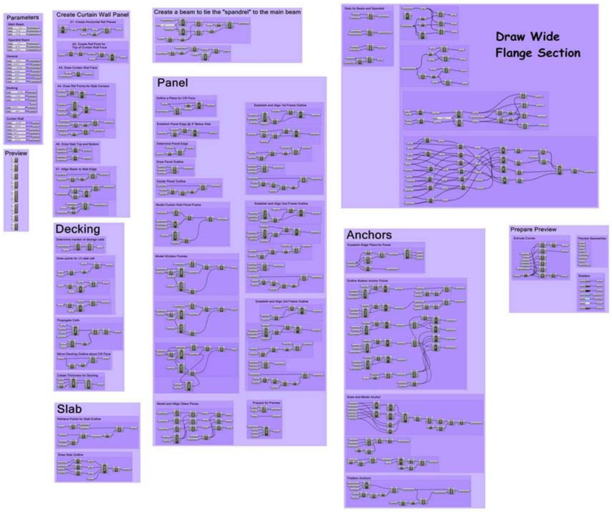



Figure 8. Partial Grasshopper script.

CASE STUDY: ADAPTIVE STRUCTURE

While parametric variations of construction components, discussed in the previous section, can facilitate development of the meta-details able to define many, or all possible, design conditions relating to a particular assembly, they can also be used to study kinetic and adaptive designs. In this case a parameter represents a constraint or degree of freedom allowing for the movement, rotation, and scale of the assembly components. By changing a single parameter, such as the angle between two structural members or their spacing, the parametric model adopts to new parametric configuration. The overall design change is driven by numeric vales and can be easily tied to parametric feeds coming from other components or assemblies. When faced with unsolvable numeric input, software responds with an "overconstrained" message indicating the problem in the assembly. This becomes a hint for students to better understand mechanical and spatial relationships of their adaptive design.

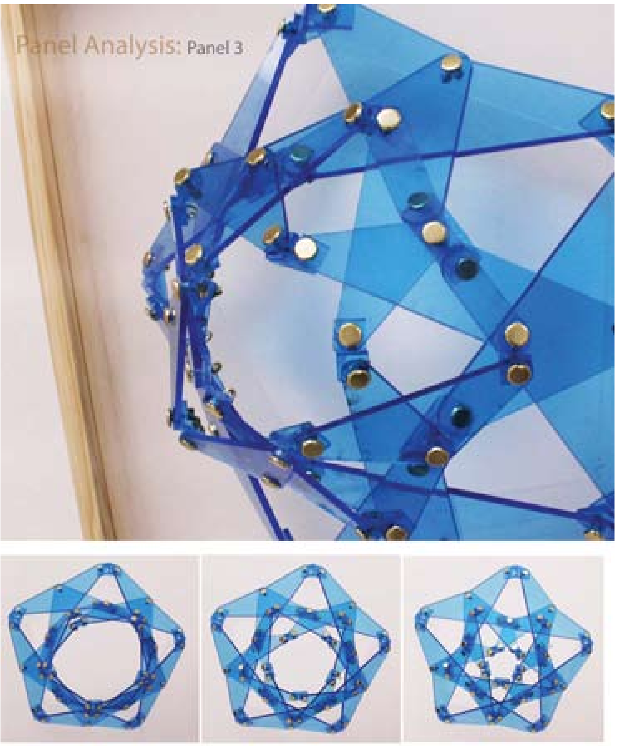


Figure 9. Adaptive structure—kinetic model.

Since the construction detail examples discussed earlier [figs.1-4] can also be seen as adaptive designs, many students pursued this line of experimentation with BIM and parametric tools.

A student-developed example of such an adaptive assembly is a façade screen system that builds on the precedents of Chuck Hubberman's work and the façade screens of the Institut du Monde Arabe in Paris designed by Jean Nouvel together with Architecture-Studio. Students developed a number of physical and computational models to test design variations and ultimately proposed three-dimensional alternatives to the conventional scissor-like hinge assembly. Their design not only brought a certain level innovation into their investigations, but also prepared them for the tedious, yet successful, resolution of a relatively complex mathematical and mechanical problem. [fig.9]

Inspired by Theo Jansen's kinetic sculptures[4] [fig.10], students investigated the design possi-

Figure 10. Strandbeest by Theo Jansen

bilities of parametrically defined adaptive systems that mimic rigged or skeletal systems used in character animation software tools. Unlike the constraint-based systems used in VFX software, BIM and parametric packages allow for more direct and precise numeric operations, including operations that can both input and output numeric values.

Using a similar approach to that of Jansen, students focused on developing individual design components and testing them with parametric tools. They focused on resolving individual assemblies and on the ways these simple assemblies could be scaled up to form larger interoperable structural systems. BIM parametric capabilities were again an effective software tool to study and evaluate adaptive designs.

One student team started by creating an exact replica, both physical and digital, of Theo Jansen's Strandbeest kinetic sculpture mechanism. They investigated the parametric possibilities of this constrained-based kinetic system. In this particular case, students looked at how specific dimensions and radii impact the kinetic behavior of the system. The final deliverable was an adaptable vertically climbing mechanism. [figs.11-12]

The presently available architectural BIM and parametric software were not optimal tools for this kind of investigation as compared to engineering tools such as Inventor. A combination of both as a single fully integrated tool would provide a better design environment.

Explorations focused on parametric constraint systems without the ability to understand acting forc-

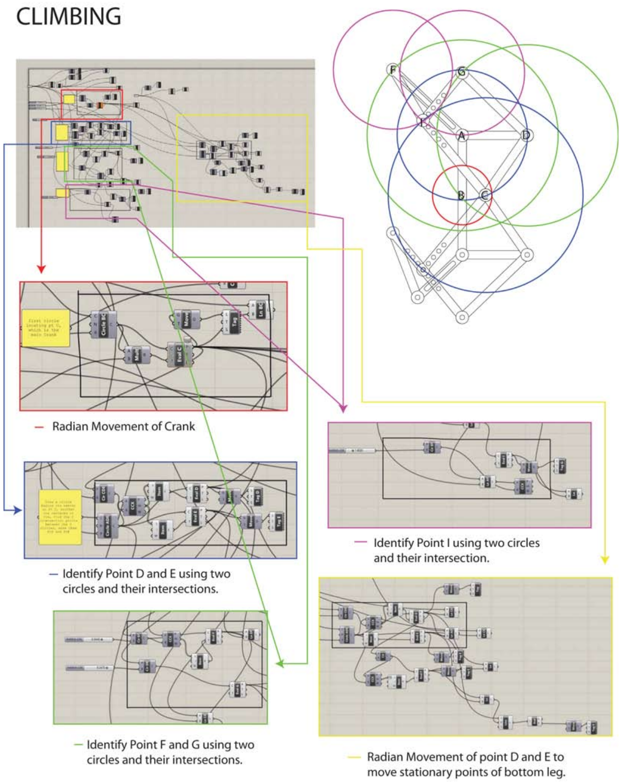


Figure 11. Adaptive structure—parametric model.

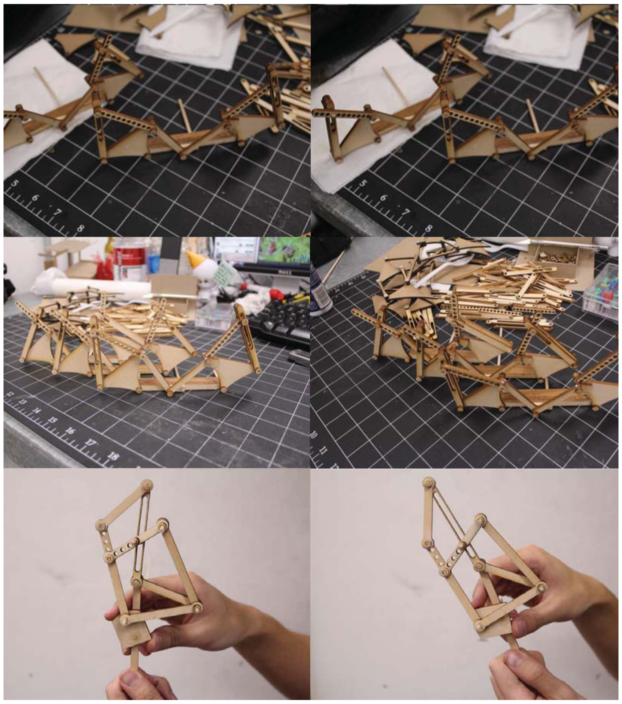


Figure 12. Adaptive structure—parametric model.

es. However, it was still a meaningful and knowledge-building experience for students involved in the project.

Another student team looked at the adaptive structure that responds to occupancy levels. In this project students were intrigued by the fact that "an area of adaptive structures often ignored is the occupancy. The changes that occur in adaptive structures generally focus on the environment (wind, temperature, time), and when they are geared towards non-environmental aspects, they are more often than not limited to non-occupational uses. For example, when there is one occupant, the space is comfortable from one person, however, when joined by a second or third person the structure adapts to become comfortable for two or three people, and so on." The design proposed by the students [figs.13,14] involved an adaptive truss "that would increase in width as it decreased in height. The walls of this structure would be attached to the ends of the truss so that when it was not under any stress, the truss would be at its highest and the space above would be most narrow."[5]

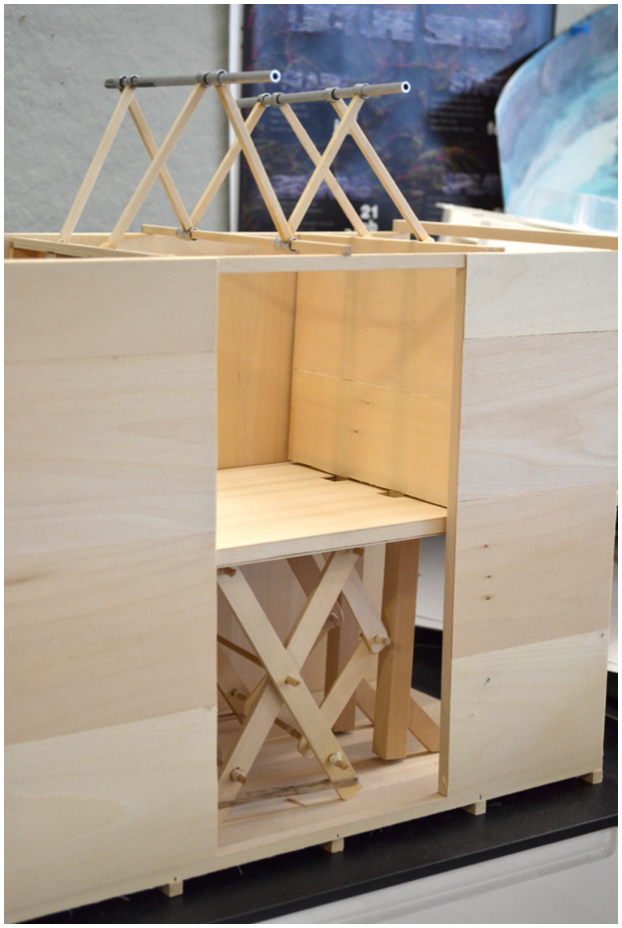
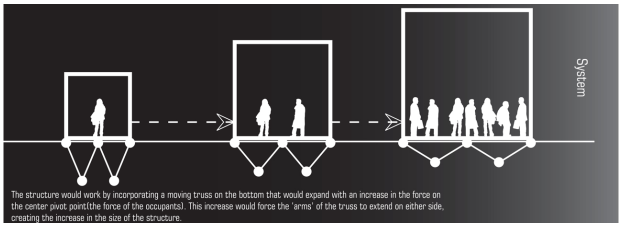


Figure 14. Adaptive structure—physical model.



The structure would work by incorporating a moving truss on the bottom that would expand with an increase in the force on the center pivot point(the force of the occupants). This increase would force the 'arms' of the truss to extend on either side, creating the increase in the size of the structure.

Figure 13. Adaptive structure--concept.

Depending on the team size and individual student abilities, some teams also developed a physical mock-up to interrelate between digital and physical designs. This was the case with the digital-versus-physical mock-up project.

CASE STUDY: MOCK-UP ASSEMBLY

While parametric design is a potent and creative approach, it reaches its full potential when combined with physically based behavior. When parametric definitions address not only expressions of inert geometries but also, or perhaps primarily, material properties and physical behavior, architecture responds to actual design drives and acquires broader relevance. In a number of projects, students experimented with computational form-emergence derived through performance simulations [fig.15-16]. They

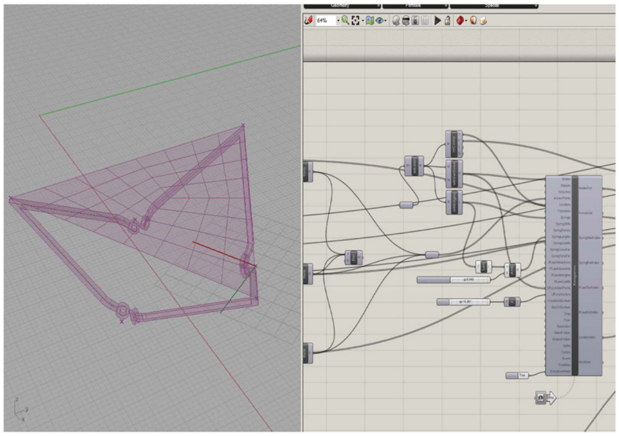


Figure 15. Testing cloth-tensile behavior with a Kangaroo component in Grasshopper.

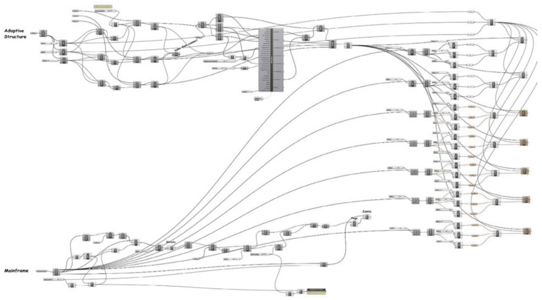


Figure 16. Parametric definition.

explored material behavior with computer analysis—designing—and later fabricated their designs using CNC machines—making [fig.17]. This combination of simulating-designing-making mirrors the traditional "learning by doing" approach.

Figure 17. CNC fabrication.

Students investigated a number of designs by parametrically manipulating their geometry. This is the point where many design studio projects end. However, in this case, considering the requirements of a building technology course, students continued their investigations by bringing a model geometry into Kangaroo, a dynamics-based component in Grasshopper. Students used a Kangaroo component for form-finding and developing a form that considers material properties and physical forces. Since this approach combines parametric functionalities with physical behavior, it allowed students to practice the interactive form-making that mimics and extends that done in a traditional context. Students could parametrically fine-tune their designs and instantaneously observe how their designs are reshaped by the impact of physical forces [figs.18,19].

Figure 18. Digital mock-up.

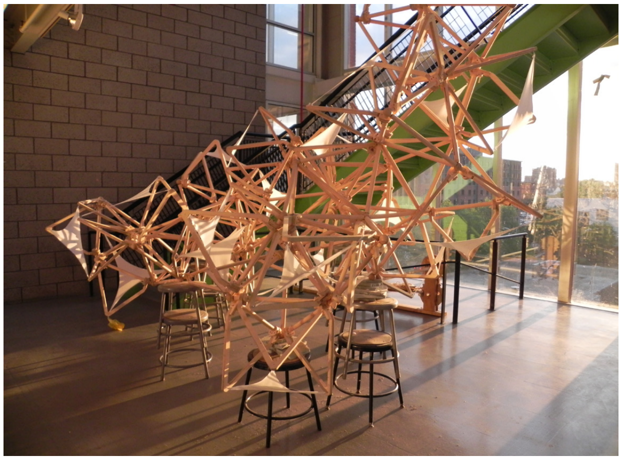


Figure 19. Final installation.

DISCUSSION

With parametric analysis, designers can immediately trace design changes and see how they impact other components in the assembly. Combining or nesting parametric components not only allows for an ease of modeling and a greater flexibility, but also allows understanding of how individual changes impact an overall design. Once a single parameter was changed in an overall, often complex, assembly of individual components, students were able to trace the propagation of changes throughout the database model and immediately evaluate the consequences of this particular change. Also, they could propose new designs through interactive manipulations of parameters and see changes propagated through the entire assembly. This dual use of parametric digital models—for understanding of a significant architectural precedent (construction knowledge building) and for speculative explorations of design propositions—allows for greater integration between building science courses and the design studio. This is particularly applicable in the upper-level comprehensive studios where generative and implemental aspects of design need to be reconciled. In parametrically defined BIM environments, students can explore designs that are native to the world of construction—that do not have to be translated or reinvented as a result of the progression from a conceptual idea to a real product.

As a result of new digital tools and developments in professional practices, students increasingly develop designs that exceed their technological knowledge. This has the potential to further fragment expertise and weaken design practice by driving it toward paper-based architecture. It also has immediate implications for the education process and specifically for changes in technology teaching methods.

Parametric design follows an interesting paradox. A common argument for BIM, and for digital design in general, is that it allows for early decision making. Thus, BIM facilitates effective design progression from the conceptual to more concrete development and implementation stages. The other argument that is often put forward is that BIM allows for deferral of design decisions exactly because of its parametric properties. This paradox can be solved with real bidirectional interoperability of BIM software. However, the real answer may lie in the way designers use software, not in its capabilities. Are we able to commit to early decision making, or would we rather procrastinate and delay thinking about details?

While both arguments are reasonable in their particular rationales, they also seem to exemplify both blessings and impediments to the design process. Depending on circumstances, early decision making may limit the procrastination and idle versioning common in architectural production, where a lack of direction or infinitesimal small variations in design alternatives effectively loop a designer into a closed design circle. Early decision making allows an experienced designer to validate his or her scenarios by introducing the constructability component into design.

At the same time, it is evident that the parametric capabilities of digital models allow for deferring specific design decisions while still considering a parametric component as an interdependent element of an overall system. In this application, parametric objects serve as intelligent placeholders for design. These placeholders can be changed if necessary, but, independent of the accuracy of their numeric values, they still function effectively as active elements of a larger interdependent system.

This property of parametric objects becomes a critical characteristic of BIM construction models, not only in understanding the models' assembly but also in applying them as explorative and generative tools for architectural design. This dual ability of BIM models—allowing designers to introduce constructional considerations in the early design stages, and later, due to the components' parametric definition, to develop variations and generate alternatives at the very end of the design process—reunites the act of conceptualizing with the act of making. It also renegotiates the boundary between design generation and design implementation. This renegotiated boundary will impact architectural practice and design team dynamics by increasing the requirement for each team member to contribute equally to the design and constructability of the project. Since design and implementation in BIM become more tightly intertwined, the separation into designer and detailers becomes meaningless. The next level of the design production integration removes architectural drafters from a design team structure.

CLOSING POINTS

The renewed interest in creating-making in architecture, as evident in works of many contemporary designers, brings a new attention to materiality and process in design. While the interest in the design process is the legacy of last couple of decades of practice and teaching, the current version of this idea moves away from the conceptual and visual toward the actual and performative. It is closely connected with the physicality of architecture through understanding the performance and impact of constructions on user behavior.

The component-based design approach for architecture, advocated in this paper, stands in contrast to past concept-centered design process as well as recent trends in which the weight of conceptual thinking, either in architecture or in the visual (fine) arts,[6] has often taken precedence over tactile or material considerations. This has been evident both with traditional (analog) and with digital-based creativity. However, recent developments in fabrication, particularly in conjunction with the parametric BIM platform, create opportunities for balancing this emphasis on conceptual thinking by bringing material and assembly considerations to the forefront of architectural discourse. Architecture returns to the realm of making, rather than conceptualizing. Traditional or digital form making not only considers the structural behaviors of particular geometries, as was the case with Antonio Gaudi's or Frei Otto's works, but also starts considering material properties that could only be partially accounted for in Otto's soap-bubble models. Computational environments not only allow for re-addressing materiality that is often missing from the design process, but also allow for asking speculative "What if…" questions. Material properties can be parametrically investigated in similar ways to tectonics or building performance characteristics such as lighting or thermal behavior.

This paper discusses where BIM software should be, not necessarily what it presently is capable. It highlights BIM potentialities, not today's level of software or designers' ability to use it effectively. The above examples show educational projects that take advantage of various software capabilities, which are already present or possible in today's practice.

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NOTES

Figure References

Figures 1,5, 19 by the author
Figure 4: Hernando Florez, NJIT
Figures 3,4: George Miller, NJIT
Figure 6, 10: Wikipedia, Creative Commons
Figure 7,8: Eli Maltzer, NJIT
Figure 9: Elvira Hoxha, Michael Middleton, Travis Stracquadanio, NJIT
Figure 11,12: Norbert Chang, Xiong Chen, Timothy Man, NJIT
Figures 13,14: Cassidy, Bryan, Brahimaj, NJIT
Figures 15-18: Benson, D'Angelo, Daring, Emara, Morrow, Piccone, Siegel, Tait, NJIT

ENDNOTES

1 A recent introduction of conceptual massing tools into BIM software, such as Revit, indicated that the industry starts responding to the conceptual design needs. Also, a simplified BIM plug-in recently became available for Grasshopper/Rhino software.

2 Karl Wallick and Michael Zaretsky, 2009

3 Image source Wikipedia, CC 3.0 by Philippe Gisselbrecht http://en.wikipedia.org/wiki/File:Centre_Pompidou-Metz_(Ete_2010)_(c)_Philippe_Gisselbrecht.jpg

4 http://www.strandbeest.com/ (accessed, June 28, 2011)

5 Quote by Cassidy, Bryan, Brahimaj, NJIT Structures 1, Spring 2011.

6 Conceptual art, as defined by LeWitt.