COLLABORATIONS
IN ARCHITECTURE AND ENGINEERING

CLARE OLSEN
SINÉAD MAC NAMARA

ROUTLEDGE

Collaborations in Architecture and Engineering

Collaborations in Architecture and Engineering focuses on team-building and problem-solving between architects and engineers to prepare you for working together in practice. It provides an overview and foundation for interdisciplinary collaboration so that you can create innovative proposals for optimization, performance, and aesthetic goals. It also shows you how to solve real-world problems and how to engage creatively with technological challenges so that you can be a productive member of any team.

The authors, an architect and an engineer, share guidelines learned from their experiences and observations on how to insure productive communication, engage in interdisciplinary discussions, and establish common goals and values. Throughout the book are many case study examples of architect and engineer collaborations—such as those between SANAA and Mutsuro Sasaki, Foster + Partners and Buro Happold, Steven Holl and Guy Nordenson, and SHoP Architects and ARUP. The book also includes a discussion about integrated project delivery (IPD) contracts and administration, so you'll be ready for better integration.

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– CONTENTS –

– PREFACE –

The authors co-taught architecture and engineering interdisciplinary design courses at Syracuse University, which were enabled through a generous National Science Foundation grant supporting Innovations in Engineering Education. The rewards of the teaching and learning experiences far out-weighed the challenges. In this book, we share our collaboration experiences as well as those of practitioners and educators, seeking to provide faculty, students, and professionals with the tools and sensibilities to enable positive collaborative experiences.

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– 1 –

Introduction
Complexity and Collaboration

WIDESPREAD change is occurring in the fields of architecture and engineering. Similar to the typological and stylistic transformations that grew out of the Industrial Revolution, new technologies and materials are revolutionizing the architecture and engineering professions, creating new working methods and sensibilities. In the 1980s, graphic Finite Element Analysis software and Building Information Modeling emerged, followed in the 1990s by Computer Aided Manufacturing software that facilitated digital fabrication. Now, decades later, we can safely say that these technologies have had and will continue to have a profound effect on curricula, design and construction methods as well as the form and performance of the work produced. New cultural, technological and social paradigms have emerged, generating new programs and building types, not to mention increased expectations of the experiences and contributions of the built environment. Consequently, the work—and work life—of architects and engineers is becoming increasingly more complex.

Technological developments in materials, construction techniques (including digital fabrication and offsite construction), and sustainable systems are just a few of the advancements that call for new approaches to design, analysis and construction work. Famously, Moore's Law predicted that the speed of our computer processor would double every eighteen to twenty-four months. "This extraordinary rate of progress means that our mobile phones now contain computers several hundred times more powerful than the one used to control the Lunar Lander for the Apollo missions."[1] This is an overwhelming but exciting notion that suggests tremendous potential for new technologies in architecture and engineering. Any number of complex forms and material assemblies that would have been too computationally expensive are now within the realm of possibility. However, given the complexity resulting from an aggregation of these systems, navigating this array requires synthesis of multiple specialties and sensibilities.

Perhaps one of the most significant outcomes of the technological shift is a growth in importance of both specialization and collaboration. Although architects are often described as generalists and engineers as specialists, the practices both require high levels of expertise, and projects at multiple scales usually necessitate teams of experts to see them through. Alliances among disciplinary experts lead to greater innovation and boundary-pushing proposals. As a result, specializations hold great value in the professional realm, making team development a crucial part of the design and construction process. Large and small firms working at all scales are increasingly forming collaborative design teams at the initial stages of the design process. Finding the "right" collaborators—those with copacetic sensibilities—can take the better part of one's career. Numerous factors contribute to the success of collaborations and the composition of the design team can make or break a project.

Despite the prevalence of collaboration in the professional realm, working in interdisciplinary groups is not always natural or easy. Personalities as well as pedagogical and professional training all contribute to the success or failure of working partnerships. Communication across disciplines can be frustrating and even adversarial. But interdisciplinary design is not only inevitable, it is essential. "Throughout history, groups of people, often without conscious design, have successfully blended individual and collective effort to create something new and wonderful."[2] Creative moments occur when making connections across boundaries, what's commonly referred to as "thinking outside the [disciplinary] box." Conversations with others outside one's discipline, approaching problems from a new perspective, have the propensity to fuel game-changing, insightful, exhilarating revelations.

Since the Renaissance period, architects, engineers and constructors have worked together, often bound through contractual obligations. Contracts have changed little in the modern period, until recently. Recognizing the increasing importance of collaboration and the efficiencies provided through Building Information Modeling and other emerging tools, the American Institute of Architects (AIA)[3] offered a new contract type called Integrated Project Delivery in 2008. IPD was developed out of a strong need for change in contractual obligations and the guidelines represent major transformations to management and working modes. Integrated delivery provides the added benefits of shared risks and rewards, easing the tension prevalent in traditional delivery modes that pit aesthetics against cost. Despite the challenges inherent in adopting new delivery methods, a growing number of practitioners recognize their potential to increase collaboration during the design and construction process and reduce costs. As a result, many feel that integrated project delivery will gain momentum and become widely pervasive in the near future. Integrative working methods, digital technologies and sustainable practices are just a handful of the issues transforming the architecture and engineering professions and it is crucial for school curricula to prepare students to be effective in the working realm.

The academy has a profound obligation to not only prepare students for professional practice, but to instill values that define a trajectory and future for the fields. Theorist and educator Dana Cuff reminds us that, "The ethos of a profession is born in schools."[4] Despite this, she goes on to say that there is a "general mismatch between the ethos of professional ideals and values (emphasized in schools) and the circumstances of professional work."[5] This has been a long-standing topic of discussion at national architecture and engineering education conferences.

Although interdisciplinary course work is advocated by both the architecture and engineering accreditation boards (National Architectural Accrediting Board (NAAB) and ABET,[6] respectively) as one way to address professional preparedness, curricular differences can hinder course outcomes. However, when designed well, interdisciplinary courses can prove to be pivotal in students' educational careers. Engineering curricula don't often provide many opportunities for open-ended design despite the fact that the real world is full of these sorts of problems. By the same token, architecture curricula require varying amounts of technical course work, but through interdisciplinary collaborations, students benefit greatly from conceptualizing projects with a higher level of technical proficiency. These synergies enhance both architecture and engineering programs by enabling students to design innovative projects with real-world possibility.

For schools that strive to impart creativity and technical skills to produce innovative design proposals augmented by integrated systems, interdisciplinary courses are necessary and crucial in the effort to impart a more holistic understanding of the practices of architecture and engineering. Furthermore, the integration of systems and design through studies of efficiencies in structure, energy or constructability, for example, contribute to a more thorough understanding of sustainability and ecology. Through the process of sharing and developing expertise, students not only gain confidence in their abilities, they also become better designers. Without question, interdisciplinary experiences are vital to preparing students for meaningful design collaborations in the professional realm.

Recognizing the importance and complexity of interdisciplinary collaboration, this text addresses the challenges and rewards of cross-disciplinary partnerships and provides real-world case studies to illustrate multiple types of collaborative working methods. It is helpful to better understand the professions and their contexts and in Chapter 2, we discuss differences and commonalities between architecture and engineering. In Chapters 3 to 12, we provide in-depth accounts of projects designed by prominent architects and engineers, demonstrating the power of integrated design to realize innovative and award-winning work. In Chapters 13 and 14, we provide an overview of platforms for interdisciplinary collaboration in practice. Finally, Chapter 15 focuses on the state of collaboration in academia, describing the ways in which schools have been both reactive and proactive in preparing students for integrated delivery methods, which will be helpful for teachers and students endeavoring to experiment with interdisciplinary design.

More broadly, the book asks fundamental questions about the current state of education and the professions of architecture and engineering. In this post-digital era where large and small offices alike are adopting new technologies and progressive project delivery methods, we reflect on how best to prepare students and offices for an evolving practice. How can architectural educators instill the importance of aesthetic design goals while emphasizing systems and sustainability? How might engineering educators foster innovation and non-linear thinking to better align education with the practice? These topics and more will be explored in *Collaborations*.

Notes

1 Peter J. Bentley, "Climbing through Complexity Ceilings," in *Network Practices: New Strategies in Architecture and Design*, edited by Anthony Burke and Therese Tierney, New York: Princeton Architectural Press, 2007, pp. 178–195.

2 Warren G. Bennis and Patricia Ward Biederman, *Organizing Genius: The Secrets of Creative Collaboration*, Reading, Mass.: Addison-Wesley, 1997, p. 2.

3 The AIA is the preeminent architectural professional advocacy organization.

4 Dana Cuff, *Architecture: The Story of Practice*, Cambridge, Mass.: MIT Press, 1991, p. 43.

5 Ibid., p. 44.

6 ABET originally stood for Accreditation Board for Engineering and Technology, but the organization officially changed the name to ABET in 2005.

– 2 –

Collaborations in Practice

When one considers the Gothic cathedrals, boundary-pushing structures and exquisite feats of architecture, it is extraordinary to the modern designer that these structures were conceived, engineered, and built under the direction of one profession, that of the stone mason. Ever since the Industrial Revolution, the proliferation of specializations required to realize a work of architecture has continued apace with an expansion of disciplinary knowledge, capabilities, and tactics. There are good reasons for this, of course: modern society requires new, widely diverse programs and building types, and an ever more complex range of technologies are available for the design, construction and maintenance of buildings. But it is worth reminding ourselves that as the professions of the architect and engineer diverged, they also became more reliant on one another for their disciplinary expertise while working towards common goals in the form of safe, habitable, beautiful buildings. Writing in the late 1800s, the great architectural historian and critic, Viollet-le-Duc, who made careful study of those very same Gothic cathedrals, cautioned his contemporaries:

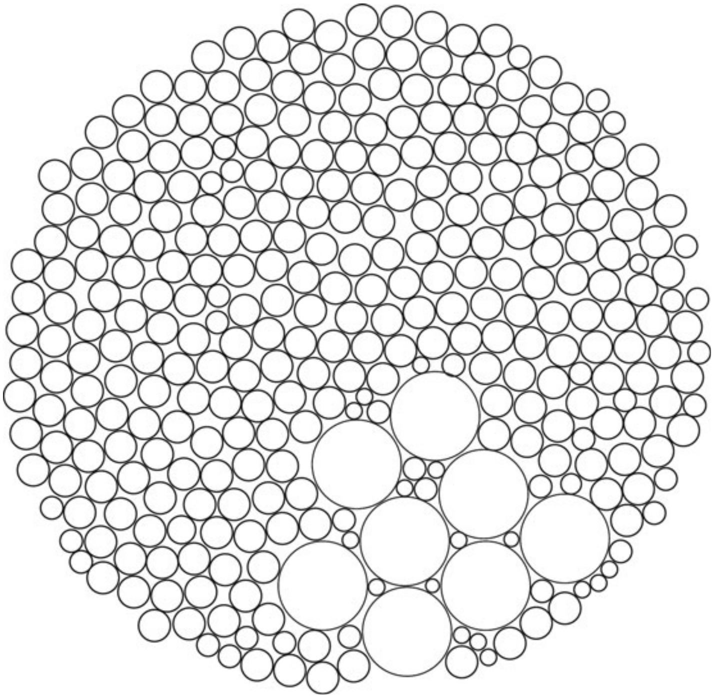
> A little reflection will show us the interests of the two professions will be saved by their union . . . Whether the engineer acquires a little of our knowledge and love for artistic form . . . or whether the architect enters upon the scientific studies and adopts the practical methods of the engineer; whether both thus succeed in uniting their faculties, knowledge, and appliances, and thereby realize an art truly characteristic of our times, the result cannot fail to be advantageous to the public and creditable to the age.[1]

This book focuses on collaboration between architects and engineers, generally structural engineers, but in some cases also mechanical engineers. Before initiating a discussion on collaboration between these professions, it is helpful to learn about the disciplinary and educational contexts that contribute to the ethos of architecture and engineering practitioners. This chapter provides a discussion about differences in the practices, highlighting the cultural, economic and historical contexts for collaboration.

Introduction to the Professions

As in all disciplines, there are numerous ways in which architects and engineers practice. Each year, about 30,000 architecture undergraduates and about 70,000 engineering and computer science undergraduates enter the workforce, but not all end up working in the fields. As discussed in Chapter 15, the curricula of architecture and engineering differ greatly and are attractive to students for a range of reasons. Ironically perhaps, both disciplines have a reputation amongst outsiders for being heavily math-oriented and focused on problem-solving. The former is less true of contemporary architecture graduates who, at least in the United States, receive considerably less mathematical training than engineering graduates. The latter is generally true and the skills learned—the ability to work through problems and provide multifaceted solutions—lend well to multiple kinds of employment and working methods.

Shifting from a broad view to a closer look at architecture and engineering practices, there is a wide range of working modes and many types of firms, defined by size and organizational structure as well as by methodologies and types of projects produced. Architecture firms are frequently characterized by the number of people employed in the office since it often correlates to the scale of projects that are being designed. A 2012 AIA survey with 2,800 practices responding found 81 percent of them had nine or fewer employees.[2] Interestingly, the largest firms with 50 or more employees, which made up 3 percent of the firms surveyed, earned 43 percent of the billings.[3]



2.1 A 2012 AIA survey found 81% of architecture firms had nine or fewer employees. Firms with 50 or more employees earned 43% of the total billings.

Drawing by Christina Hoover.

These statistics indicate that an overwhelming majority of architecture professionals work in smaller firms, and the quality of work life depends upon office culture and organization as well as the type of work being produced. Since architecture is both a creative endeavor and a commodity, architects generally operate within the duality of artist/organizer. Job responsibilities in architectural offices range from technical aspects of architectural production, which include specification writing and code analysis, to creative endeavors such as spatial design and representation. The smaller the office, the more likely that the employees are "wearing many hats" in order to carry out the work.

Similar diversity is found among engineering practices. Workplace cultures vary widely depending on the scale of firm and focus of the work. Contemporary engineering practice is wildly diverse both in terms of the type of work and methodological approaches. As diverse as the roles performed in the field of architecture, engineers engage in endeavors including research and development of new technologies and systems, design and analysis, construction management and marketing. Since the Industrial Revolution, engineering jobs have grown more than any other sector and engineers work in many facets of society, not strictly engineering firms. The Bureau of Labor and Statistics survey of civil engineers indicated that in 2010, 4 percent of engineers worked alone, 50 percent in professional, scientific or technical services, 1.5 percent in educational institutions, 29 percent in government, and 15 percent were working in other types of industry.

Stereotypes of engineers and architects and their work abound: The engineer makes it stand up, the architect makes it look good. The architect's lofty design ambitions are thwarted by engineers' column grids and bracing. While there might be some kernel of truth at the heart of these caricatures, the reality of interdisciplinary collaboration is more complex and nuanced. Since the professions are so interdependent, collegiality and mutual respect must form the basis of any partnership. Traditionally, however, there are structural impediments that hinder successful collaboration between engineers and architects, and both disciplines have much to learn from those in the vanguard of integrated design practice.

In the context of the design and construction of buildings large and small, the dominant division of labor between the disciplines is generally understood as an architect-led process with structural engineers, mechanical engineers, and other experts providing disciplinary expertise along the way. Often in traditional practice, the design is relatively well advanced by the architects before other disciplines are engaged in the process. The particular engineer–architect pairings and the case studies we examine in this book, however, are different. We focus on particularly well-integrated and successful collaborations that have resulted in buildings that would have been impossible without the involvement and expertise of multiple disciplines: in their realization, the buildings are greater than the sum of their parts.

Symbiotic Collaborations

While works of architecture are generally identified by their architect and not their engineer (the Eiffel Tower is a notable exception), it is not difficult to argue that masterful works of architecture are not achievable without significant contributions by engineering collaborators. Pritzker Laureate, Rem Koolhaas, for example, began collaborating with Cecil Balmond at Ove Arup in 1985. Of this partnership, Koolhaas has said, "Our growing intimacy with each other's disciplines—in fact, a mutual invasion of territory—and corresponding blurring of specific professional identities (not always painless) allowed us, at the end of the eighties . . . to defrost earlier ambitions and to explore the redesign and demystification of architecture, this time experimenting on ourselves."[4] The symbiosis of their relationship has clearly had a profound effect, not only on the work, but also on the growth of Koolhaas and Balmond as creators.

The proximity of the engineers and architects working together certainly facilitates a comfort level and ease of communication, crucial aspects of successful collaboration. When architects and engineers don't work well together, both aesthetics and function suffer. One might find structure in the way of a spatial sequence, or air conditioning that needs to run 24/7 because site strategy and passive cooling systems were not considered early in the design process. The contemporary movements towards in-house collaborations and Integrated Project Delivery highlight the growing need to work synergistically. Integrating aesthetics with structure, sustainability, and systems requires multiple voices at the design table to share perspectives and expertise.

Collaboration and Relationships

Communicating with experts outside one's discipline can be challenging and sometimes frustrating, so when architects find engineers with whom they work well, who understand their design goals and intentions, they often partner with the same colleagues for decades. Louis Kahn and August Komendant designed innovative reinforced concrete structures together from the 1950s until Khan's death in the late 1970s. Many of the structurally expressive skyscrapers of the Second Chicago School were the result of the long collaboration at Skidmore Owings and Merrill (SOM) between architect Bruce Graham and engineer Fazlur Kahn.

Similarly, Renzo Piano and Peter Rice worked on numerous projects together, with the Pompidou Center in Paris an especially successful example of their work. Rem Koolhaas and Cecil Balmond have designed numerous structurally ambitious projects including Maison à Bordeaux and CCTV. Like Koolhaas and Balmond, Toyo Ito and Mutsuro Sasaki's collaborative work is so well integrated that it is impossible to distinguish the engineering from the architecture. Steven Holl and Guy Nordenson have a decades-long working relationship and their writings about their work reflect a deep mutual understanding and reciprocal inspiration in their working methods.

2.2 Skidmore, Owings, & Merrill, John Hancock Center, Chicago, IL, 1970.

Photograph by Seth Anderson.

Conversations with almost all of the architects and engineers interviewed for this book described the importance of long-standing relationships; learning how one's collaborators think and communicate forms the basis of successful collaborations. Bruce Gibbons, head of the Building Structure practice for Thornton Tomasetti Los Angeles, believes strongly in early collaboration, but also recognizes, "It's always easier to collaborate with someone you know. When working with people for the first time, communication can be a major challenge."[5] Engineer Hans Schober of Schlaich Bergermann und Partner, speaking about the Berlin Hauptbahnhof design, claimed that years of experience working with the architects, von Gerkan, Marg und Partner (gmp), prompted them to invite Schlaich Bergermann und Partner to the design team. Schober also said that his firm agreed to be involved because they knew gmp were open to the kind of structurally honest designs that Schlaich Bergermann und Partner so favors.[6]

A number of engineers interviewed also cited the importance of proving their value or earning their place in early conversations of the design process. Richard Garlock, structural engineer at Leslie E. Robertson and Associates, explained that when he had been successful in suggesting an innovative solution or money-saving alternative in previous collaborations, he was much more likely to be invited to contribute early to subsequent projects.[7] Guy Nordenson reported a similar phenomenon in a current collaboration with Renzo Piano[8] and Kurt Clandening of John A. Martin Engineers voiced parallel observations.[9] Nearly all contributors, engineers and architects alike, said that the respect and mutual recognition for each other's disciplinary expertise were vital and among the most important aspects of fruitful collaboration.

Collaboration and Communication

Many factors contribute to who we are, how we work and how we interact with others. Harvard University experts in group behavior say that, "Different brain systems may have evolved not only to work together within a single head, but also to work together between heads—that is, so that different systems are not only 'plug compatible' within a single brain, but also across brains."[10]

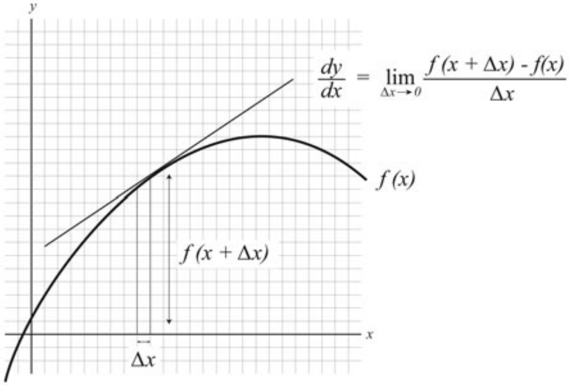
This creates an interesting image, but it also points to some critical issues for understanding collaboration. Firstly, people have different brain systems and are differently skilled.

2.3 Harvard University researchers describe how brains are "plug compatible" to enable collaboration.

This is what's so wonderful about the nature of collaboration. Individuals have diverse capabilities, desires, and backgrounds so teamwork provides an opportunity to fortify efforts by bringing multiple skill sets together to achieve goals. There is a catch, however. The very differences that can lead to synergies and epiphanies can be a huge source of frustration between collaborators, especially when working interdisciplinarily. People are drawn to study particular fields for a wide range of contextual, environmental, and personal reasons. Subsequently, differences in educational experiences compound dissimilarities in personalities.

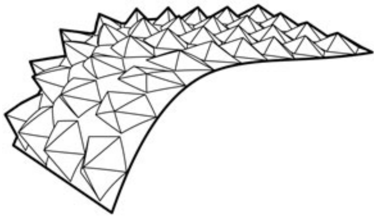
This raises an important issue, which is that even though there are certain generalizations that can be made about the differences between architects and engineers, every person is unique, with individual goals, values, techniques, and quirks. Differences in communication and working methods can be one of the most challenging aspects of working in teams. It is important to note that the disciplines of engineering and architecture have different, but overlapping disciplinary vocabularies. The same word might mean very different things to architects and engineers. Words with fluid and useful disciplinary meaning in architecture such as *differentiation*, *articulation*, *atmosphere*, *continuity*, *discontinuity*, *integration*, and *variation*, have altogether more prosaic and perhaps more rigidly defined meanings in the world of the engineer.

As these examples suggest, the disciplinary vocabulary one learns in school is not necessarily helpful when communicating with colleagues in other fields. Learning how to communicate effectively is a skill one develops over time through mentorship and observation. Ken Sanders, on the Board of Directors at Gensler, says, "The most important skill set is the ability to collaborate, by far."[11] Sanders also remarks that technical skills can be taught on the job, but the ability to collaborate is "the most important criteria for new hires . . . The human piece is the harder piece."[12] Of course, communication skills can also be learned on the job, but working well with others does not come naturally to all people. When asked about communicating with his structural engineering colleagues, Ben Mickus, Associate at Skidmore Owings



2.4 A visualization of *differentiation* as understood by engineers.

Drawing by Christina Hoover.



2.5 A visualization of *differentiation* as understood by architects.

Drawing by Clare Olsen.

and Merrill (SOM), notes that the burden is on architects to learn how to communicate effectively in order to integrate structural reasoning with architectural goals.[13] SOM has an unwritten mentorship program where junior colleagues and Directors participate side-by-side in roundtable design discussions and after a meeting, a mentor might explain why something was said, thereby passing along communication methods.[14] At the interdisciplinary firm, communication skills are highly valued and assessed in the annual performance reviews.

Collaboration requires more than clear communication, however. David Farnsworth of ARUP, speaking about the B2 BKLYN case study, made an incisive comment: "In today's working environment, one needs to be able to collaborate, be quick to get on the right side of a job, have a willingness to take responsibility, but also know when to share credit."[15] These behaviors can be challenging, but extremely important when working in teams. Architecture, especially, has a reputation for being ego-driven, so collaborators need to know when to advocate for their project goals, but also support team members by negotiating and making trade-offs. Stereotypically, architects and engineers value different results, but aesthetics and efficiency don't have to be pitted against one another, and credit given to an engineer's contribution need not diminish the architect's reputation. Ideally, researchers claim, "In a true creative collaboration, almost everyone emerges with a sense of ownership."[16] Successes are achieved when multiple experts contribute, moving the project beyond the boundaries of a single discipline. By pushing the field and challenging oneself, each person can feel reward in the accomplishment of the new.

Not all people in the design world value innovation and creative collaboration, but for architects and engineers who do, communication is pivotal to the design process. Hanif Kara, structural engineer, co-founder and design director of AKT, points out, "Just as good architecture relies on good clients, good architects make for good engineering. They understand the basic technical role played by engineers, but can also push engineers to think of questions they have not thought of themselves. In this way, good architects know how to get the best out of engineers."[17] Along these lines, engineer George Keliris of Buro Happold states, "[Being a good engineer] is not just about structural calculations, but about creativity. [At Buro Happold], we value new ideas, innovation, and difference,"[18] which is a major reason that Buro Happold is widely known for collaborating on some of the world's most innovative projects. Finding the "right" collaborators to contribute to the creative process is of utmost importance.

The Cost of Collaboration

SOME architects may feel that since the engineer's fee often comes out of the architect's compensation, it makes financial sense to establish early collaboration only on the more technically complex projects. Morphosis Architects often collaborate with engineers from the very beginning of projects, but at the same time, the firm is mindful of budget restrictions that can hinder early collaboration on all projects. Chandler Ahrens of Morphosis describes,

> The typical relationship between architects and engineers is that the engineer is a consultant to the architect, so their fee is coming out of your fee. You want to use that wisely . . . Not every project requires a really elegant solution . . . If it is a more straightforward project, you might use a engineer that is really good at optimizing cost, especially if that structure is going to be clad and hidden . . . With a more experimental project, you are going to tend to go with a higher-end engineer and if it is an experimental project that probably means you have the budget to support that.[19]

Many interviewees cited the role of project finances in shaping the nature of collaboration. Garlock describes that the contract structure and client's willingness to pay for engineering design both factor into the time in which engineers are involved in the design process. Of course, the earlier engineers are brought on board, the more potential they have to influence the design process.[20] Steven Holl and others note that waiting until later in the design process to consult with technical experts can be a false economy since design services are a small part of the overall budget in comparison to materials and construction.[21] In larger projects especially, collaborations resulting in minor savings in materials costs would more than compensate for extra engineering fees at the start of the project. In Chapter 14, a discussion about contract types and alternate project delivery methods promises to address structural impediments to collaboration.

In-house Collaborations

WITH many architects and engineers who work at the cutting edge of their respective disciplines engaging in ever more integrated design work, it is not surprising that some offices are moving towards in-house collaborations. The 2012 AIA firm survey found that 6 percent of architectural offices' employees are engineers.[22] In "In-house Engineers Make Sustainable Design Work Better," Novitski describes interviews with architects who have created in-house positions for engineers to insure early incorporation of ecological thinking and sustainable systems. Novitski's interviews with architects working in A-E firms were generally positive. For example, one architect quoted by the study's authors, "believes this new practice has profoundly changed the firm. He concludes, 'We believe the engineers are making us better architects, and architects are making engineers better, too.'"[23]

The trend to employ engineers in-house is nothing new for one of the most prominent integrated firms, Skidmore Owings and Merrill (SOM is discussed in greater detail in Chapter 10). Since the firm's founding, SOM's architects and engineers have collaborated from the beginning of the design process, and have become internationally known for designing buildings where the architecture and structure cannot be separated—the engineering is critical to the architectural experience and vice versa.[24] As associates at SOM point out, "This spirit of architectural and engineering collaboration feeds the development of conceptual and technical invention to this day at SOM, leading to new structural and architectural paradigms."[25]

Foster + Partners provides a more recent example of integrating in-house engineers, although an integrated approach has been central to Foster + Partners work since the inception of the practice in 1967. The addition of in-house engineers in 2010 was a natural progression from a reorganization in 2005 that restructured the office into multidisciplinary teams. In the first reorganization, the employees were distributed into six design groups, as well as a number of support teams, all led by senior partners. Mouzhan Majidi, Chief Executive, stated that, "Significantly, the first year of our new collaboration was the practice's most successful ever. During that period we won thirteen international competitions and forty-one design awards—a record for us— and we opened offices in New York, Istanbul and Madrid."[26] With the success of the team structure, two in-house engineering groups were established a few years later. Having partnered on numerous projects with Piers Heath's firm, PHA Consult, the office was purchased and many of the engineers went to work in Foster + Partners' London Riverside studio. Piers Heath is now a Senior Partner and leads the Environmental Engineering team. Foster + Partners currently employs more than 50 engineers in house. Xavier De Kestelier, a Partner at Foster + Partners and joint head of one of the support groups, the Specialist Modeling Group, describes how "The engineers sit with the architects—they really integrate by proximity—there isn't a separate department. There isn't a different review to look at the engineering and the architecture—they are reviewed at the same time . . . the integration within our office at all levels has worked quite beautifully."[27] With the engineering team in-house at Foster + Partners, the collaborators can chat in real time on a daily basis, streamlining communication and therefore the efficiency of project design and development. Integrating engineers into the practice has resulted in an interesting transformation in the way that the engineers work and communicate with their architect collaborators. Foster + Partners has a long history of valuing technology and model-making and the firm has one of the largest fabrication shops in London, including numerous 3D printers that run day and night.[28] De Kestelier says that since the engineers are now integrated into a highly technological, research-oriented environment that relies heavily on representation, the engineers have quickly become adept at visual communication and model-making, as well as utilizing the 3D printers to test ideas. The supporting infrastructure and partnerships have enabled a rich working environment that sparks a "hunger to continuously improve."[29] Significantly, Norman Foster describes the office collegiate structure as one of the design projects of which he's most proud.[30]

Collaborative Case Studies

The case studies that follow this chapter provide an in-depth study of the collaborative design process. Seeking an understanding of how projects are realized, the authors interviewed dozens of architects and engineers about their design processes and working methods. Although many—sometimes 20 or more—offices may have worked on a project, each case study usually profiles the partnership of two firms: the architects and structural engineers.

For a few case studies, a third party was interviewed because one of the initial interviewees suggested that those consultants (façade, MEP, the local architect, construction managers) were an integral part of the story. We interviewed innovators—people who are making significant contributions to the fields of architecture and engineering. The case studies themselves were usually chosen by the interviewees. The focus of the case studies is not the project itself, but rather we are interested in the people who designed them and the way in which their collaborative processes are manifest in the final outcome.

Numerous commonalities arose in this research both in terms of the people we interviewed and the work they are doing. Many of the projects are innovative and experimental, where designers developed new forms and experiences through the use of new technologies and materials. The projects also share sustainability goals, which were a driver in seven of the ten projects. For example, Cooper Union is LEED Platinum, ARTIC is on track for LEED Platinum, and the Port House is on track for a "very good" BREEAM rating. It was striking how many practitioners are also teachers. This tendency often translated into research-based practices where innovation is valued. With links to academia, practitioners find new hires from their classrooms where they are able to more carefully assess students' skills, working methods and collegiality.

It was also remarkable to find so much loyalty and interdependence. The majority of the case studies describe long-standing collaborations, architects and engineers who have worked together on multiple projects. It is disappointing to note, however, that when we talked to engineers, they were usually quick to describe the working relationship with the architects; however, a couple of architects were not as forthcoming with acknowledging the contributions of their interdisciplinary colleagues. Of course, we hoped to find only positive examples of collaboration, and while the majority were, there were a very few outlying instances (which we did not highlight) where individuals spoke negatively (and regretfully) about the collaborative process. Collaboration is not easy and it's not always productive. There are many methods of working with a team, and the case studies provide insights into the collaborative process through examples of largely successful collaborations that tackled complex technical constraints and laudatory architectural ambitions.

In terms of program and scale, five of the ten case studies are larger infrastructural projects: an airport in Jordan, two port projects (in Taiwan and Belgium), and two regional transport stations (in California and Germany). The group also includes three housing projects (MIT Simmons Hall, B2 BKLYN and SPG Shanghai) at different scales. Educational and institutional projects are included with 41 Cooper Square and the Toledo Museum of Art Glass Pavilion. With the exception of the Glass Pavilion, the projects are medium to large in scale. Five out of ten projects are completed, three are under construction, one will break ground soon, and one project was a competition proposal that will never be built in the form represented, although the research and design have proven rather influential for subsequent projects in the office.

As described in the introduction, practicing in the design world today is extraordinarily complex. The case studies provide a snippet of the design processes that contributed to realizing the projects. In SOM's competition project, for example, a multidisciplinary team worked for months, researching the site, soil and systems, creating custom scripts to model and analyze the form, inventing a now patented solution to make concrete more sustainable and lightweight . . . and the list goes on. The case studies presented here do not attempt to exhaustively illustrate the breadth and depth of the long list of collaborators and their input into each project. Rather these studies are an effort to unpack the complex and multifaceted nature of these designs by focusing on two to three of the primary disciplines involved with the goal of understanding the influence those collaborators and their collaborations had on design processes and final outcomes.

It has been incredibly rewarding to connect with the hugely talented individuals who contributed to these projects. We hope you too will find them inspirational.

Notes

1 Eugène Emmanuel Viollet-Le-Duc, *Lectures on Architecture, Volume II,* trans. Benjamin Bucknall, Boston: James R. Osgood and Co., 1881, p. 72.

2 American Institute of Architects, "2012 AIA Survey Report on Firm Characteristics," AIA Business Report. www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab095792.pdf (accessed March 18, 2014).

3 Ibid.

4 Rem Koolhaas, "Speculations on Structure and Services," reprinted in *Rethinking Technology: A Reader in Architectural Theory*, ed. William Braham and Johathan Hale, London: Routledge, 2007, pp. 354–357, p. 340.

5 Bruce Gibbons, Interview by authors, phone interview, Los Angeles, CA, July 8, 2013.

6 Hans Schober, Interview by authors, phone interview, Stuttgart, June 19, 2013.

7 Richard Garlock, Interview by authors, phone interview, Princeton, NJ, June 25, 2013.

8 Guy Nordenson, Interview by authors, phone interview, New York, NY, June 14, 2013.

9 Kurt Clandening, Interview by authors, phone interview, Los Angeles, CA, May 24, 2013.

10 Anita Williams Woolley, J. Richard Hackman, Thomas E. Jerde, Christopher F. Chabris, Sean L. Bennett, and Stephen M. Kosslyn, "Using Brain-based Measures To Compose Teams: How Individual Capabilities And Team Collaboration Strategies Jointly Shape Performance," *Social Neuroscience*, 2(2) (2007): 96–105, p. 103.

11 Ken Sanders, "Collaboration & Performance/Materials & Building Practices," Lecture, New Constellations, New Ecologies for Association of Collegiate Schools of Architecture, San Francisco, CA, March 20, 2013.

12 Ibid.

13 Ben Mickus, Interview by authors, in-person interview, San Luis Obispo, CA, March 15, 2013.

14 Eric Long, Interview by authors, phone interview, San Francisco, CA, April 23, 2013.

15 David Farnsworth, Interview by authors, phone interview, New York, NY, June 4, 2013.

16 Warren G. Bennis and Patricia Ward Biederman, *Organizing Genius: The Secrets of Creative Collaboration*, Reading, Mass.: Addison-Wesley, 1997, p. 28.

17 H. Kara, "On Design Engineering," *Architectural Design*, 80 (2010): 46–51.

18 George Keliris, Interview by authors, phone interview, London, UK, June 21, 2013.

19 Chandler Ahrens, Interview by authors, phone interview, St. Louis, MO, May 2, 2013.

20 Garlock, Interview by authors.

21 Steven Holl, Interview by authors, email interview, New York, NY, August 6, 2013.

22 American Institute of Architects, "2012 AIA Survey Report on Firm Characteristics."

23 B. J. Novitski, "In-house Engineers Make Sustainable Design Work Better," *Architectural Record, Business Practice*, archrecord.construction.com/practice/business/0910practice.asp (accessed August 2013).

24 SOM, "Fazlur Kahn," SOM Legacy, https://www.som.com/fazlur-r-khan (accessed August 2013).

25 K. Besserud, N. Katz, and A. Beghini, "Structural Emergence: Architectural and Structural Design Collaboration at SOM," *Architectural Design*, 83 (2013): 48–55.

26 Mouzhan Majidi, *Catalogue: Foster and Partners*, Munich: Prestel, 2008, p. 327.

27 Xavier De Kestelier, Interview by authors, phone interview, London, UK, June 18, 2013.

28 Ibid.

29 Ibid.

30 *How Much Does Your Building Weigh, Mr. Foster?*, Film, New York: Art Commissioners, 2012.

– 3 –

41 Cooper Square

Client	The Cooper Union
Architects: Morphosis	Thom Mayne, Silvia Kuhle, Pavel Getov, Chandler Ahrens, Jean Oei, plus team
Associate Architects	Gruzen Samton, LLP
Structural Engineers	John A. Martin Associates, Inc.
Mechanical Engineers	IBE Consulting Engineers, Syska Hennesy Group
Façade Consultants	Gordon H. Smith Corporation
Lighting Consultants	Horton Lees Brogden Lighting Design, Inc.
Graphics	Pentagram
Construction Management	F.J. Sciame Construction Co., Inc.

41 Cooper Square was designed and constructed in collaboration with the above-named individuals and many more designers, engineers and specialists. This case study will focus specifically on the collaboration between the architects at Morphosis, structural engineers at John A. Martin, and mechanical engineers at IBE.

Morphosis

MORPHOSIS was founded in 1972 by Thom Mayne, an architect educated at the University of Southern California and the Harvard Graduate School of Design. Morphosis began as a small, renegade practice focused on thinking through making and became widely known in the architectural community and beyond for exquisite drawings and models of the early restaurants and houses they designed, mostly located in the Los Angeles area. The firm has become known for large institutional and governmental projects, including the passively cooled and naturally lit Federal Building office tower in San Francisco and the iconic California Department of Transportation headquarters (Cal Trans) in downtown Los Angeles. As the firm became more prolific, so did the international acclaim, highlighted by Thom Mayne's receipt of the Pritzker Prize in 2005.

Architectural theorist and critic Jeffrey Kipnis characterizes the firm: "Morphosis' schemes have been aggregates of discrete, articulated components arranged in machinelike contrivances."[1] Recent behemoth-scale projects seem to draw energy from the surrounding context, hovering in a state of becoming, in the form of giant metal-clad towers, cantilevered extensions, and dynamic, moving skins. Through partnerships, research, and invention, Morphosis has created bold, expressive structures while pushing the field through advancements in sustainability and technology. The firm triumphed over a slew of international offices in a competition to design the first building for Cornell's Tech campus on Roosevelt Island in New York City. Mayne explains that the commission marks an opportunity to imagine the future of higher learning[2] for the highly technological, net-zero campus. Mayne once described his design process as "a deliberate schizophrenia between instinct and logic,"[3] or art and function. Both are clearly present in the subject of the following case study.

John A. Martin

Based in Los Angeles, John A. Martin, founded in 1953, specializes in structural design services and undertakes much of their work at the institutional and infrastructural scale, that is, high-rise offices, transportation facilities, retail, government, healthcare and educational buildings. They employ over 500 people in eight offices across the US and China. They describe their focus as "efficiency, constructability and value."[4] Notable projects for which they have provided structural design include: the Staples Center and LA Live Complex in Los Angeles, the Frank Gehry designed Walt Disney Concert Hall in Los Angeles, the new international airport in Bangkok Thailand, and the recent Tom Bradley Terminal expansion to LAX airport.

IBE Consulting Engineers

IBE stands for "Ideas for the Built Environment," founded in 1999 in Los Angeles by engineers Alan Locke and John Gautrey, who began their careers at ARUP in London. It is an interdisciplinary practice that provides services in mechanical engineering, energy systems, lighting design, and façade performance among others, all with a strong emphasis on sustainability through conservation of resources and energy.[5] Notable recent projects include Hall Estate Winery designed by Frank Gehry, Nevada Museum of Art with architect Will Bruder, Charles David Keeling Apartments, a housing complex at UC San Diego's Revelle College designed by Kieran Timberlake, and the Coop Himmelb(l)au building for the Akron Art Museum in Ohio. The relationship between IBE and Morphosis is a long-standing one, with

Thom Mayne having worked with both principals for many years, starting with their time in the LA offices of ARUP.[6] The Advanced Technology group at IBE, which specializes in designing intricate buildings and their systems, worked on the design of 41 Cooper Square.

The Collaboration

In 2004, Morphosis was commissioned by The Cooper Union for the Advancement of Science and Art to design a new building located at 41 Cooper Square in New York City. Recognizing the complexity of the program and systems required, the architects enlisted structural engineers from John A. Martin and MEP engineers from IBE to partner with them from the beginning of the project. Chandler Ahrens,[7] Lead Designer for Morphosis on the project, argues (as have many others in this book) that successful collaboration between architects and engineers is often a product of an ongoing relationship. "It takes time to educate your engineers about how a company like Morphosis works. It is not a typical company—it takes a few projects, so it is hard to switch and work with someone you don't know."[8] For a relatively complex project like 41 Cooper Square, Ahrens makes the case for collaboration as early as possible in the process. He describes both the structural engineer, Kurt Clandening from John A. Martin, and the mechanical engineer, Peter Simmonds from IBE, who collaborated on the project as "engineers who really know how to work with architects." Jean Oei, a member of the design team from the start of the project who also served as Morphosis' Job Captain all the way through the project, agrees with Ahrens, stating, "We had the same mindset: everyone wanted to do the most sustainable, best building you could put out there. It was very much a collaborative project—it could not have happened otherwise."[9]

Describing the early weeks and months of the project, Ahrens notes the height restrictions on the site, the very particular mechanical needs of a university building with labs, and the impact those things might have on the structure. Given these needs, it was incredibly important to have mechanical and structural experts in the very first meetings:

> You want to identify what the limitations are going to be as early in the process as possible. Cooper Union is in New York City, thus you are extremely confined. Every square inch matters, and the building is a lab, so there are really intensive MEP constraints. You are potentially dealing with chemicals, so the fume hoods etc. will really drive design. The zoning envelope had already been established. We knew we needed to fit nine stories in the envelope, that sets your floor to floor height, and we knew we needed mechanicals on the roof . . . The mechanical engineer is telling us every fume hood gets its own dedicated exhaust so we needed a stainless steel duct going from every fume hood going all the way up the building, welded and sealed off . . . they needed to track horizontally and then find a large shaft all the way up to the roof, so that is really going to affect your floor to ceiling heights. The

> labs have a lot of equipment, so you need a ten foot ceiling, and you have structure to consider; it all has to fit. So you have all of these requirements pushing against each other. At the same time we had the structural engineer in the room, and he's saying that this can't be a steel building, it is just not possible with all these constraints, it has to be flat slab concrete, which is not typical for this building typology in New York City.

Ahrens describes these early in-person meetings as "absolutely critical." While architects have enough training and experience to have some idea of the answer, it is important not to "go too far down the road" without having the engineers involved, he says; "I think pride can get in the way; you don't want to sound stupid, or naive, but it is so important to ask the slightly naive questions, because if you ask a different question, you get a different answer. I think that is where a lot of exploration happens."

Structural engineer Kurt Clandening observes that it is important for engineers not just to give the architects what they ask for, but rather to engage them in such a way as to establish what they *need* for the project to succeed, to understand the big picture. This is something he learned in his first engineering position where he worked with a number of engineers who had previously worked at SOM where collaboration is very much part of the culture (see Chapter 10).[10] He echoes Ahrens' sentiment that earlier is better in terms of collaboration and appreciates Morphosis' willingness to engage in the beginning stages, arguing that it improves the project in the long term:

> Morphosis is probably one of the few architectural firms that I've had the opportunity to work with that really understand the benefit of a collaborative design very early on. With Cooper Union, I would go over and sit in their offices for about four hours every Friday morning. We would sit, they would talk about what they were thinking, and how they were evolving one area of design, telling me their goals for the project. Instead of just telling me what they wanted from me, they would communicate their big idea and let me provide structural input that complemented that idea—and that allowed me to come up with fairly creative (and what I considered unique) solutions to things they likely didn't even know were problems yet, but they knew they had problems they wanted to solve. They included me in that problem-solving iteration.

Clandening also agrees with Ahrens that context drives the nature of the collaboration. The kind of collaboration he describes with Morphosis is by no means universal for his practice. "You have a shorter leash with certain types of projects . . . definitely as sub-consultants we absorb and mimic a little bit of our clients' style." When working with architects on projects that are a little more driven by a program, he finds there are fewer opportunities for the kind of "out of the box" thinking, than happened on the Cooper Union project. For example, when the firm designs hospitals, the programmatic needs, the code requirements, and the clients' outlook mean the process is far more constrained. Since early collaboration is not the norm for most firms, Clandening contends that it is not a process with which all engineers feel truly comfortable. "For a lot of engineers this is a difficult process because there is no answer. They [the architects] are not giving you direction, they are asking you to think way outside the box, think way beyond just details and calculations." On the Cooper Union project, Clandening based most of the preliminary structural concepts on intuition and experience as opposed to generating detailed calculations, "because they [Morphosis] were looking for more conceptual input. It really was as collaborative process, and I believe it allowed me to provide valuable input as opposed to just telling them the column size for a predetermined grid, and I think they realized the value early on. It [41 Cooper Square] is really an integrated design." He further asserts, as have other engineers interviewed for this book, that engineers sometimes have to prove their merit in earlier projects to convince their architecture partners of their value to a project in order to spur greater collaboration in the future:

> I think that the engineers here at JAMA, including myself, find the Morphosis type of collaborative processes much more rewarding and we take more ownership of the process and the project at the end. So I encourage everybody to do that extra little bit and you may find that the architects will respond by including you more in that up front process.

Mechanical engineer for the building, Peter Simmonds, has worked for IBE with Morphosis on many projects, and also teaches environmental control courses to students of architecture at USC. He concurs that their collaborative process is very open and communicative: "It was very successful in as far as there was a complete understanding among the design team of what the goals were."[11] He remarks, as did Ahrens, that although the project is critically acclaimed in contemporary architecture for the formal and experiential quality of the work, the average person might not realize that, because it is a laboratory building, mechanical concerns and the attendant code requirements were a driving force in the design. He also asserts, as did many other designers interviewed for this text, the significance in effective collaboration of a shared respect for disciplinary expertise. "We have a good understanding, there is also a respect for each trade. They [Morphosis] have respect for how we work . . . they always had time to listen to our point of view, when you work with someone who is listening and who is understanding what your constraints are, that makes it a lot easier." Speaking about the value of communication and the importance of appreciating the "other" discipline's goals, he jokes about the stereotypical position of an engineer: "I am an engineer, things are black and white, the last thing you want to do is discuss it with the architect," but for truly successful collaboration he insists:

> I think the one thing I have learned, not from my education, but in my experience, is that you have to know how to discuss the project with the architects. There is no point in coming with a lot of math to an architect. That is just not effective. They

are looking for the big picture, or the artistic solution; you have to learn how to communicate with them.

It is clear from the responses of these team members that the collaborative process for 41 Cooper Square was truly integrated from the very beginning and that the communicative approach of the architects and engineers involved was key to the success of the project.

The Project

Completed in 2009, 41 Cooper Square houses laboratories, an exhibition gallery, an auditorium, lounge and multipurpose spaces for The Cooper Union for the Advancement of Science and Art, a 150-year-old, highly selective college in downtown Manhattan that produces engineers, architects and artists. According to Clandening, well-integrated collaboration also requires the right kind of client. The Cooper Union, as an architecture and

3.1 The Cooper Union for the Advancement of Science and Art, Morphosis Architects, John A. Martin and IBE, 41 Cooper Square, New York, New York, 2009.

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engineering school, wanted "to create an image that the school itself is forward thinking, and then they were fortunate enough to get an architect like Morphosis who has that same philosophy, so you have a client that wants something unique, they want something that makes a statement. Morphosis is good at doing that, it is really a function of finding the right architect, the right client, and the right project."[12]

Nine stories high, the building has a double-height entrance leading to a dramatic atrium stair, 20 feet wide, that ascends through the first four floors of the sculptural void which extends the full height of the building, drawing daylight through the entire structure. Writing in *Architectural Design*, critic Jayne Merkel describes this space: "It is as if an inverted tornado had blown through the structure, tearing apart a neat concrete staircase so that the steps were bent and the roof of the building was blown away."[13] This central volume is lined with a steel lattice scrim giving vertical form to the space and privileging the staircase as a defined space of circulation and social condensation.

The exterior of the building is wrapped in a double-layer façade, an inner glazed layer with an outer skin of stainless steel perforated panels. This outer layer is lifted one story above ground level and is slashed open in rough vertical and horizontal cuts on the front façade. These moves symbolically open the structure to the city with which the institution is so entwined.[14] At moments of openness in the façade, hints of the concrete structure behind can be seen. These dual strategies of layering and slicing can be seen in the original architect's concept drawings for the building.

3.2 Model of the design showing the structural system and the atrium. Morphosis Architects, John A. Martin and IBE, 41 Cooper Square, New York, New York, 2009.

© Morphosis Architects.

3.3 The atrium with the steel mesh scrim surrounding the void. Morphosis Architects, John A. Martin and IBE, 41 Cooper Square, New York, New York, 2009.

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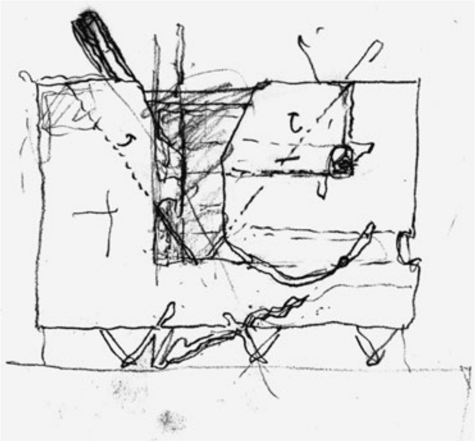
The outer surface has operable panels, which are mechanized to allow additional daylight and solar gain into the space during certain times of the year. During peak heating and cooling days the panels are closed. The exterior is a living membrane that is utilized to reduce the energy consumption of the building.[15]

The structure of the building is largely a conventional flat plate concrete structure with vertical columns 30 feet on center. The four deviations from standard construction are the columns at the ground level which are aggressively diagonal and also out of plane, the entry corner where the column was removed, the central atrium for which the slabs must cantilever out to form the edges, and the southwest corner where the concrete structure is notched out to make a light glass box that holds an exit stair.

Clandening reports that the design of the cantilevered slabs that surround the atrium provides an example of the way the early and collaborative conversations among the design team led to design solutions that addressed multiple concerns at once:



3.4 Architect's concept sketch. Morphosis Architects, John A. Martin and IBE, 41 Cooper Square, New York, New York, 2009.

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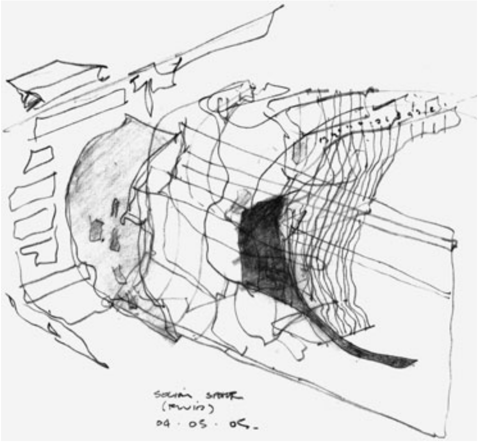

3.5 Architect's concept sketch. Morphosis Architects, John A. Martin and IBE, 41 Cooper Square, New York, New York, 2009.

© Morphosis Architects.

3.6 Note the diagonal columns at the base are out of plane. Morphosis Architects, John A. Martin and IBE, 41 Cooper Square, New York, New York, 2009.

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3.7 Note the column-free corner. Morphosis Architects, John A. Martin and IBE, 41 Cooper Square, New York, New York, 2009.

© Sinéad Mac Namara.

> It is a cast-in-place concrete building, but in the atrium for the stairs they [Morphosis] wanted to have the ability to attach a lot of steel elements, but they didn't want a lot of ugly imbeds [where steel is bolted into a concrete surface]. I suggested we take all of the slabs that cantilever out into the atrium and taper them down to 8 inches, and then embed an 8-inch channel, which also serves as a form stop when you pour the concrete. Then you could weld whatever you wanted to it. In our mind that was a very simple solution that allowed them to get very accurate dimensional control because concrete formwork is always hard to control, but a prefabricated channel could be bent in the shop to Morphosis' tolerances. It was a very convoluted shape: it was an amoebic shape in the building and the opening changed on every floor. So this strategy allowed Morphosis to get what they wanted, which was a very high degree of control on a slab edge and attach things to it and you didn't have to see the attachment.[16]

3.8 The atrium under construction. The slab edges, the connecting stairs and the installation of the steel lattice. Morphosis Architects, John A. Martin and IBE, 41 Cooper Square, New York, New York, 2009.

© Morphosis Architects.

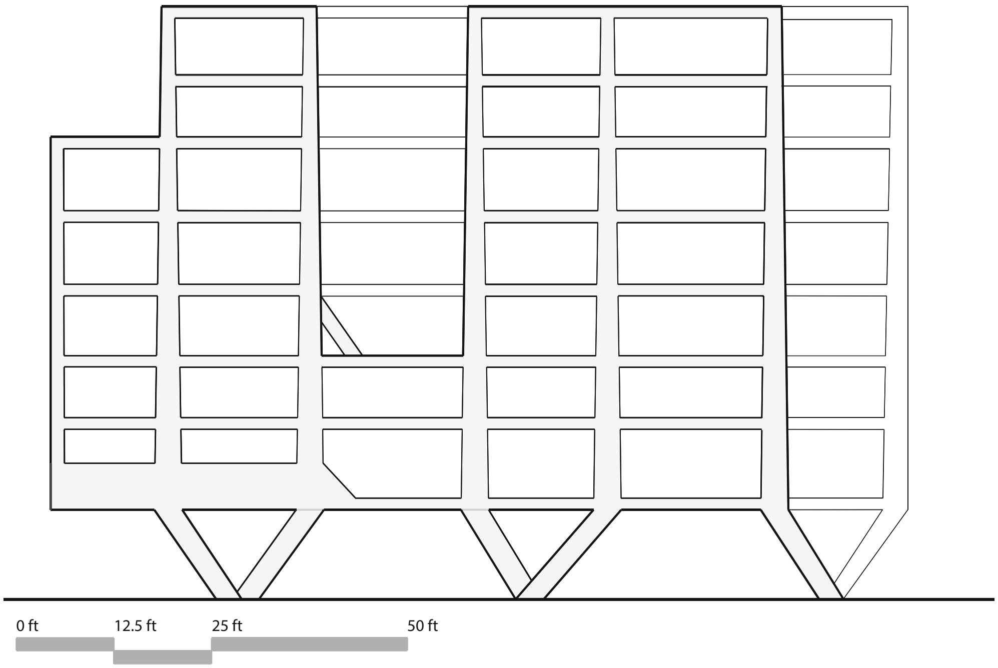
To make this strategy work, the engineers had to carefully check all slab thicknesses at the edges (some edges were just five feet past a column and some were up to 12 feet away, so the structural depth requirement would have been different) so they ultimately just made the last five feet of the cantilevering slab the same. While this approach might sound complex, the contractor reported that it was ultimately a very economical solution. It was an effective tactic because it allowed the builders control in the construction process and they could avoid everything that normally goes wrong in buildings that are geometrically complicated.[17] Even though this was among the most complex slab edges they had ever built, it was actually cheaper than comparable projects. Clandening contends that the reflexive response of some engineers (even some of his own colleagues) to this issue would have been to tell the architect to use the imbeds and not to bother looking for another solution; but his philosophy, which he tries to impart to the junior engineers that work with him is, "If someone asks you a question, don't answer the question, answer the reason behind the question. So I was asking myself, not just how do we connect to the slab edge? But rather, how do we develop a system that gives them complete flexibility and complete control?" The architects at Morphosis were pleased with the solution and ultimately requested that the engineers oversize the channel a little bit so all the slabs have a short toe-guard lip on the edge that became part of the architectural language of the building.[18]

Oei describes that atrium as both the heart of the project and exemplary of the AECO collaboration:

> The atrium in particular is a really great example of how all the different disciplines as well as the trades, construction manager, and the client came together to collaborate . . . The school is comprised of engineering, architecture, and art and in the old building, there was no place to hang out and meet so in the design of this building, there was a lot of focus on a social space so this was the heart and soul of the project . . . Sciame, the CM [construction manager], played such an important role in our design team and was really crucial in helping to execute this atrium. When we first started talking about material options, we came up with this idea of using GFRG [glass fiber reinforced gypsum] and they were very gung ho and supportive in helping us realize our vision . . . Together with the team, we designed this entire atrium within a very, very tight budget, but it was seamless. It was a a hugely successful example of all the disciplines coming together.[19]

The entrance to the building is on the northwest corner and from the beginning of the design process the architects were clear that they did not want a column at that corner. The eight floors above have a very regular column grid and it would have been quite expensive to cantilever each of the corner slabs and edge beams, so there is an eight-story column that is supported on the very tip of the cantilevered floor that carries the weight of the corner on each of those eight floors above. The difference between one of the edge beams in the upper floors at this location and the cantilevering transfer girder that would be necessary at the first floor to make the column-free atrium is a twenty-fold increase in bending moment. Thus the transfer girder would have to be very deep, potentially lowering the ceiling in the lobby, which was not in keeping with the open entrance that the architects envisaged:

> We worked with them for a long time; I understood their overall goal was not to have a column on the corner. But I had to work within the geometry they had and there was some suggestion that we'd tell them they could not have it or we'd tell them "you have to have a column over here" but I resisted that. We found out that that location on the second floor was all faculty offices, while the other floors were labs. We figured in those offices everybody would have a desk so they'd need a four-foot-high wall above the floor anyway. So I suggested instead of a transfer girder below the slab, we could upturn it and take advantage of the space no one would be using. This way we could give them a very high vaulted opening for the lobby, and when you look at it you can't tell that there is a transfer girder there because it doesn't stick down below the slab, it pops up into the space above, where it works with the program.[20]



3.9 Structural grid just behind the front façade. The lighter sections are recessed. Note the deep transfer cantilever under the column-free corner and the recessed zones of structure that correspond to the vertical opening in the stainless steel skin (center) and the notch for the stair tower (right). Morphosis Architects, 41 Cooper Square, New York, New York, 2009.

© Christina Hoover.

This cantilever was a pretty adventurous move structurally. The day before the construction supports were removed from underneath, Clandening says the on-site team was worried about its safety. He told them it would deflect ¾ of an inch when they took out the shoring, and when they called him back afterwards they reported only ⅝ of an inch in deflection. Instances like these, Clandening asserts, demonstrate why it is so vital that engineers and architects build up trust in one another. The consequences of structural failure are potentially catastrophic and neither side wishes to be held responsible, but too much conservatism can stymie innovation.

Another successful detail of the building that was facilitated in collaboration between the structural engineers and architects working on the design was the stair tower on the southwest corner. In early meetings with Clandening, Ahrens was clear that the intent was to have a glowing beacon of light on that corner. To that end, they wanted a light translucent structure. It was decided to notch out the concrete structure from the corner and build the stair tower from steel. Even then, Clandening explained that the columns would have to get bigger on the lower floors to handle the potential for buckling from the increasing compressive force as you move down through the building. This was not satisfactory for the architects who wanted the lightest and most regular structural geometry possible. "I said, well how about instead of building the stair up from the floor we put one big cantilever beam at the roof and then hang

3.10 The translucent stair tower on the south west corner of the building. Morphosis Architects, John A. Martin and IBE, 41 Cooper Square, New York, New York, 2009.

© Sinéad Mac Namara.

the stair from that, then the hangers are very small because they are all in tension and they are all the same size all the way down, so that entire nine-story stair is hanging from the roof. This way we gave the architects what they wanted: it was light, it was airy, it wasn't made out of concrete, and it was all the same, all the treads all the hangers are the same size." In the final design, he reports, this stair was cheaper than a standard exit stair would have been, because the hangers used so much less material than the columns would have done. Cost considerations may seem like a lamentably pedestrian or functionary aspect of a highly acclaimed project on which to focus, but as Clandening observes, "You can only do great architecture and keep doing it if you can consistently deliver for the price that the client is willing to pay." In fact, Morphosis is noted in the industry for their capacity to deliver high-end architecture without the budget

3.11 Interior being winched into place, note the perforated steel ceiling panels behind. Morphosis Architects, John A. Martin and IBE, 41 Cooper Square, New York, New York, 2009.

© Morphosis Architects.

overruns commonly associated with high-profile work.[21] Doubtless a contributory facet of this ability is their integrated and collaborative approach to technical aspects of the design.

As noted above, the mechanical engineering for this building was a major part of the design process and in particular the venting of fume hoods required significant ductwork. To stay within the allowable building envelope and still retain ten-foot floor to ceiling heights, the mechanical systems had to be carefully designed. One of the innovative systems employed were radiant ceilings. Simmonds explains:

> [41 Cooper Square] was one of the first projects to use the reemerging technology of the radiant ceiling for heating and cooling. When you propose a radiant ceiling the big challenge is condensation and that makes a lot of designers and clients nervous. Morphosis and The Cooper Union were 100% behind us to design that system, which we did and there haven't been any problems with it. Morphosis worked to integrate the ceiling: they designed a ceiling with perforated steel panels that works with the radiant system. We put the heating and cooling panels above that the whole thing went together like a Swiss watch.[22]

Simmonds observes that the radiant ceiling eliminated enough ductwork to allow an extra floor to be included over what a normative system would have supported. He also remarks that all the systems in the building were so carefully designed with LEED platinum status in mind, that the building uses 46 percent less energy than the minimum code compliance threshold. For the clients this meant a saving in energy costs of over $200,000 per year.[23]

A high-tech building for a storied institution of innovation and art, at 41 Cooper Square the collaborative disposition and disciplinary expertise of all its designers combined to make an extraordinary building. Morphosis' vision is skillfully executed by a diverse group of designers working in collaboration.

Oei remarks, "Thom [Mayne] has said that Cooper was one of those dream jobs where everyone got along . . . everyone wanted to build a really good building the best they could. The budget was actually very stringent—and the only way it could happen was through the really close collaboration and integration of all the different disciplines."[24]

Notes

1 Jeffrey Kipnis, "Cincinnati Impressions," in *Morphosis IV*, New York: Rizzoli, 2006, pp. 14–19, p. 14.

2 Robin Pogrebin, "Thom Mayne of Morphosis Is Chosen for Cornell NYC Tech – NYTimes.com," Breaking News, World News & Multimedia, http://www.nytimes.com/203/05/09/arts/design/thom-mayne-of-morphosis-is-chosen-for-cornellnyc-tech.html (accessed August 2013).

3 Thom Mayne, Yukio Futagawa, and Yoshio Futagawa, *Morphosis*, Tokyo: A.D.A. Edita, 1997.

4 "Mission," John A. Martin & Associates, Inc., http://www.johnmartin.com/about/mission (accessed August 22, 2013).

5 “History,” IBE Consulting Engineers: Ideas for the Built Environment, http://www.ibece.com/about/history/ (accessed August 22, 2013).

6 Chandler Ahrens, Interview by authors, phone interview, St. Louis, MO, May 2, 2013.

7 Chandler Ahrens has since left Morphosis to focus on teaching at Washington University and his practice Open Source Architecture.

8 Chandler Ahrens, Interview by authors.

9 Jean Oei, Interview by authors, phone interview, Los Angeles, CA, February 10, 2014.

10 Kurt Clandening, Interview by authors, phone interview, Los Angeles, CA, May 24, 2013.

11 Peter Simmonds, Interview by authors, phone interview, Los Angeles, CA, May 30, 2013.

12 Clandening, Interview by authors.

13 Jayne Merkel, “Morphosis Architects’ Cooper Union Academic Building, New York,” *Architectural Design*, 80(2) (2010): 110–113.

14 Morphosis Architects, “Cooper Union,” *Morphopedia – The Online Encyclopedia of Morphosis*, http://morphopedia.com/projects/cooper-union (accessed August 21, 2013).

15 Peter Simmonds, Interview by authors, email interview, Los Angeles, CA, September 4, 2013.

16 Clandening, Interview by authors.

17 Ibid.

18 Ibid.

19 Oei, Interview by authors.

20 Clandening, Interview by authors.

21 Pogrebin, “Thom Mayne.”

22 Simmonds, Interview by authors, May 30, 2013.

23 Ibid.

24 Oei, Interview by authors.

– 4 –

Berlin Hauptbahnhof

Client	Deutsche Bahn AG
Architects	von Gerkan, Marg und Partner (gmp) Meinhard von Gerkan and Jürgen Hilmer
Structural Engineering	Schlaich Bergermann und Partner, IVZ/Emch+Berger
Lighting Design	Peter Andres + Conceptlicht GmbH
Mechanical Services	Ingenieurgesellschaft Höpfner

The design of the Berlin Hauptbahnhof involved many firms and individuals, but the focus of this discussion is on the partnership between Schlaich Bergermann und Partner and von Gerkan, Marg und Partner.

Schlaich Bergermann und Partner

Schlaich Bergermann und Partner is a German engineering firm co-founded by Jörg Schlaich, a German structural engineer who studied civil engineering at Stuttgart University and the Technical University of Berlin, and Rudolph Bergermann. Although formally enrolled as an engineering student, Schlaich attended architecture courses and would have tried to qualify in both areas but for the difficulty in resolving the competing timetables of the two schools that were situated in two different campuses in Stuttgart. He was heavily influenced by his sister, who trained as an architect at Stuttgart University and later at IIT under Mies van der Rohe. She introduced him to many structural engineers whose work was of interest to architects, such as Robert Maillart and Pier Luigi Nervi.[1]

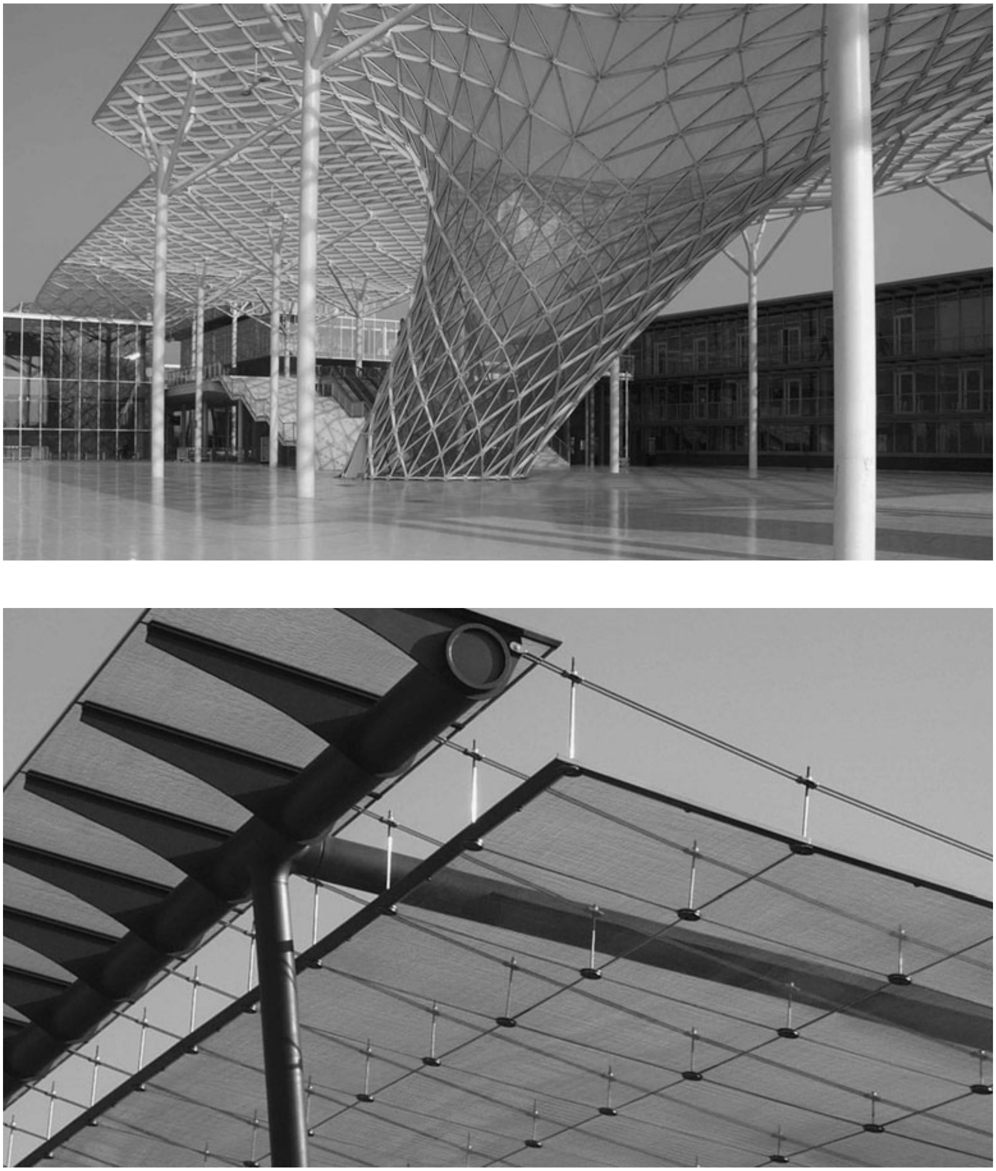
Schlaich is a professor at Stuttgart University and a partner in the firm he founded. In 1972, he was the engineer of the roof for the Munich Olympic Arena designed by fellow German architect/engineer Frei Otto. The resolution and construction of the pre-stressed cable net roof required the development of one of the first computer programs to help design such structures to be used at this scale in the professional practice.

4.1 The cable net structure consists of saddle-shaped surfaces supported by edge cables and masts, which are in turn anchored by cable stays. Frei Otto and Schlaich Bergermann und Partner, Munich Olympic Arena, Munich, Germany 1972.

© Schlaich Bergermann und Partner.

Under Schlaich's direction, the firm has designed and built many pedestrian bridges in a spare, elegant style that is always structurally expressive. This work won the firm many accolades including multiple awards for innovation and design. Schlaich emphasizes the importance of the pedestrian bridges to the firm's practice due to their intimate scale. As structures that humans interact with closely, he believes they must be as carefully designed as any building. This humanist concern for the user is at the forefront of the firm's philosophy.[2] The engineers were among the first to experiment with grid shell glass roofs and façades, concentrating on form-finding to create shapes that would self-structure, integrating the load-carrying structure and glass mullions as one system. They also experimented with forms that could be stiffened with the minimum of extraneous structure such as pre-stressed cables and thin struts, thus minimizing structure in order to maximize the transparency. The firm's early work in this area was inspirational to architects and designers internationally.

Evident in all the firm's work is the expected concern for efficiency and economy common to most engineering firms, but Schlaich is also clear in his desire to pursue "the poetics of



4.2 (a) Logo and Vela, a free form grid shell roof acting as connecting links between exhibition pavilions, Schlaich Bergermann und Partner in collaboration with architects Massimilano Fuksas, and Rom + Paris, Milan Trade Fair, Milan, Italy, 2005. (b) Glass Canopy at the Light Rail Station Plaza, a suspended glass roof, Schlaich Bergermann und Partner in collaboration with architects Auer and Weber, Heilbronn, Germany, 2001.

© Schlaich Bergermann und Partner.

lightness."[3] There is a "stylistic awareness" in their work that has drawn the attention of many in the architectural design field.[4] Schlaich and his colleagues exhibit a distinct preference for structural forms in which the members act entirely in tension or compression, claiming they are the most "honest." The firm's work makes heavy use of cable nets, tensile fabric structures and other solutions that enable formal expression while minimizing structure. In particular, Schlaich extols the virtue of the shell as the most honest because "[it] lends itself less than any other structure to attempts to hide inadequate design under camouflage or cladding."[5]

von Gerkan, Marg und Partner (gmp)

Based in Hamburg, but with offices across Europe and Asia, von Gerkan, Marg und Partner (gmp[6]) are architects with an established history of innovative work at institutional and infrastructural scales. They are one of the largest and most prominent architecture firms in Germany. Founded in 1965 by Meinhard von Gerkan and Volkwin Marg, they have completed noted designs for stadia, exhibition and conference centers, airports, train stations, and museums internationally. In recent years the firm has completed designs for several airports in Germany, governmental and cultural projects in both Vietnam and India, multiple soccer stadia in Brazil ahead of their World Cup hosting, and many transportation and institutional projects across China including a number in Liang New City, for which they did the master planning.

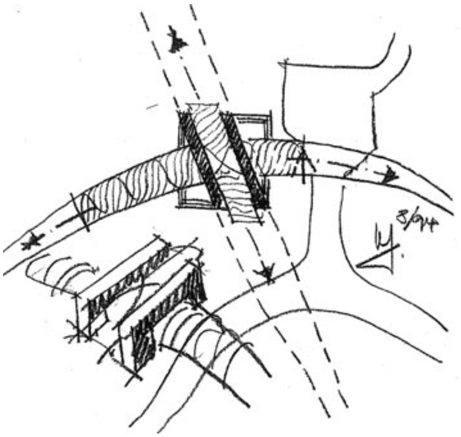
Writing about his work, Volkwin Marg says "if there is a general ethos, then it is that investment in architecture is much too expensive, for it just to be short lived."[7] The firm has developed a reputation for work that is neither avant-garde nor populist, preferring instead to emphasize design competence and purposefulness.[8] The partners describe their architectural interpretation as "characterized by the Vitruvian ideals of solidity, longevity and beauty."[9] Their design philosophy is one of simplicity, responsiveness to site and structural rationality.[10]

> With a critical distance from recent architectural expressions, we try to avoid expressionist forms, which are only derived from artistic caprice, without reference to use, construction and functionality . . . The development of appropriate and acceptable answers and solutions for problems demands an openness for dialogue and the adaptation of one's standpoint to changing conditions.[11]

Both of the founders are also active in teaching, having held numerous professorships over the years, and gmp sponsors the Academy for Architectural Culture, a Hamburg-based institution that supports education and research in architecture and design.

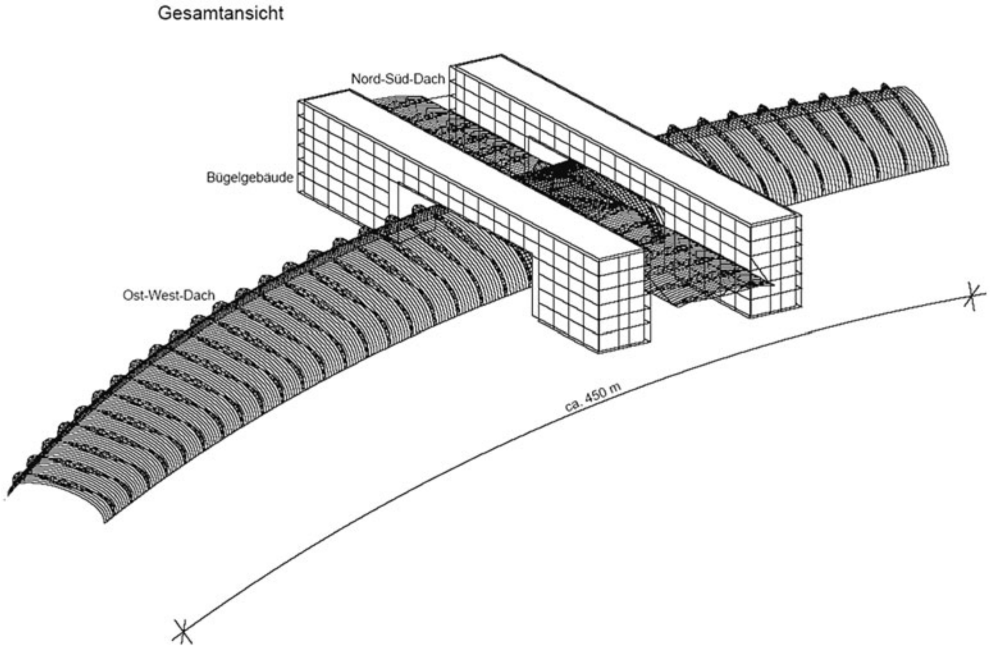
The Project

When Berlin became the capital once again of a reunified Germany, there was a need to create a new transportation hub in the center of the new Berlin, close to the newly reinstated government buildings. This facility would reconnect the tram and underground systems in the city along with the regional, national and international train systems. On the site



4.3 Architect's concept sketch for the Berlin Hauptbahnhof. The east–west arched roof spans the overland tracks for the regional, national and international trains, the office tower runs north–south as do the underground tracks hidden below. von Gerkan, Marg und Partner and Schlaich Bergermann und Partner. Berlin, Germany, 2006.

Design Sketch by Meinhard von Gerkan, von Gerkan Marg und Partner.



4.4 Drawing of the final design for the Berlin Hauptbahnhof. von Gerkan, Marg und Partner and Schlaich Bergermann und Partner, Berlin, Germany, 2006.

© Schlaich Bergermann und Partner.

of the old Lehrter station, just to the west of where the wall had stood, overlooking the River Spree, the site for the new Hauptbahnhof (Central Station) was found. The proposal called for 175,000 square meters of space over five platform levels.[12] The facility serves over 300,000 passengers on 1,200 trains every day[13] and is the largest train station in Europe.[14]

As is common for many significant public buildings in Germany, a design competition was held; gmp invited Schlaich Bergermann und Partner (SBP) to work on the competition with them, and their entry took first prize. The two firms had worked together many times before, on projects including bridges, airports, and stadia such as the new roof installed on the 1936 Olympic Stadium ahead of the 2006 Soccer World Cup.

The architects of gmp's winning vision for the station has a pair of axes; the overland tracks run along the east–west axis and the office and retail building that straddles them runs north–south to mark the orientation of the underground tracks below. These formal gestures of the structure mimic a stitch that is knitting the fabric of East and West Berlin back together.

The east–west tracks are under a 320m long arched glass roof reminiscent (in form if not materials) of the great European train stations of the nineteenth century. Originally designed to be 450m long, the arch starts with a span of 46m on the approaching tracks, flaring out to a span of 66m inside the station to make room for the platforms in between. The height of the arch also varies from 14.5m to 16.5m as the arch flares out.[15] The three-dimensional variation of this roof would have been all the more dramatic had it been built to its planned length. The client dictated the shorter roof length for time reasons rather than cost, and the architects at gmp were disappointed by this decision.[16] Nonetheless it is a striking form; from a distance this platform roof that accommodates six train tracks and the associated platforms, looks almost

4.5 Berlin Hauptbahnhof. von Gerkan, Marg und Partner and Schlaich Bergermann und Partner, Berlin, Germany, 2006.

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4.6 The interior of the Berlin Hauptbahnhof looking south. von Gerkan, Marg und Partner and Schlaich Bergermann und Partner, Berlin, Germany, 2006.

© Marcus Bredt.

like a singular sheet of glass carefully curved over to span the distance. Only up close does the intricate structure reveal itself, and the primary structural elements are thoughtfully pulled back from the end of the roof to emphasize this sharp, thin, elegant edge. The north–south axis consists of a pair of taller buildings that bridge over the surface level tracks; suspended between these buildings is a glass canopy roof that covers the mezzanine levels of shopping and access to the underground lines below. Recessed back from the edge of the canopy roof on both ends is a suspended glass façade. Inside the building, the comparative weight of the office building with its exposed steel exoskeleton contrasts with the light filigree structure of the glass roofs and walls.

The Collaborating Team

Hans Schober, the lead engineer for SBP on the Berlin project, emphasizes the importance of the long-standing relationship between the architecture and engineering firms to the collaboration process, in particular because it often means that the architect will be willing to bring the engineer into the process earlier. Speaking generally about collaboration between architects and engineers, he says: "It is very clear, as the engineer you have to start to work with the architect at the conceptual phase. This is the phase where you can be innovative and contribute new ideas."[17] He characterizes the traditionally dominant industry paradigm where the architect makes all formal and design decisions in the early stages without any input from the engineer and the engineer merely calculates and sizes members for what the architect has designed as "totally the wrong way." Rather:

> When we work together, it is often the case that the architect has ideas about the structure, different than those of the engineer, and it stimulates the engineer to innovate. In turn, when the architect takes input and learns from the collaboration about good structural ideas, the architect is also stimulated by the engineer. If you don't exploit this potential, you miss a lot of new ideas and opportunities . . . It is very important that both disciplines work together from the very beginning, I must say, many of our architects come to our office because they know that we work in this way. It is also good for an engineer's reputation, if architects know that the engineer has great input and brings innovation to the design.

Schober observes that the history of gmp working together with SBP influenced both their decision to bring them onto the project, and to involve them from the very beginning. He also credited the architects of gmp and their interest in structural form as an important facet of their work together:

> Because we had worked with [gmp] . . . many times before . . . they knew we would collaborate well. These architects are receptive to a structure that expresses the design, therefore we have a relatively tight relationship . . . Working with gmp is a very good fit for us, we were a team from the beginning, this was very, very important. The conceptual design phase was more than one year and we worked very closely with them.

Architect Jürgen Hilmer, who led the project for gmp, concurs:

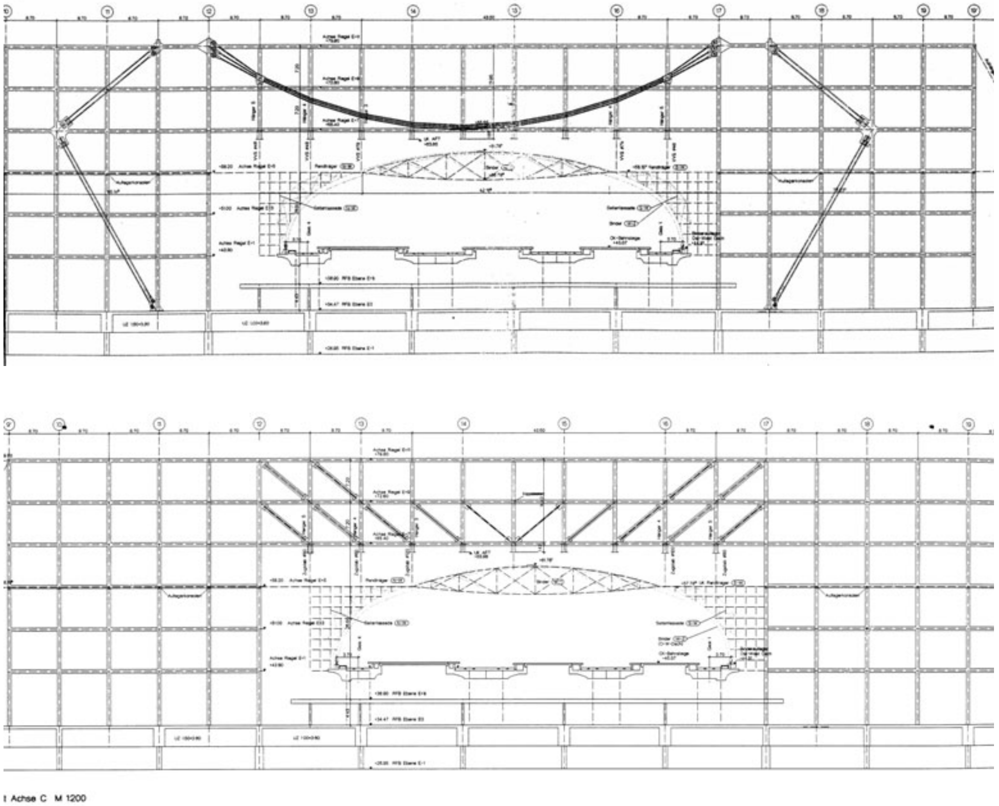
> In the years we have worked together we have been able to develop a deep sense of professional familiarity and a common general understanding of architecture and construction principles, upon which our years of teamwork is founded. Our philosophy of design, which can be characterized by simplicity and diversity,

> uniformity and variety and structural organization, coincides with Schlaich Bergermann and Partner's philosophy. That is the only means by which one can produce a design in cooperation with another planner.[18]

Schober describes the project as an excellent example of collaboration between the architect and the engineer in that there are elements of the final design where the architect's vision is absolutely primary and elements that come entirely from the structural principles of the engineer. The office building design, with its exoskeleton of structure in a square grid sitting markedly proud of the façade, was an important part of the architect's competition-winning proposal. However, Schober describes this design as presenting two significant challenges to the structural engineers. "Here we had a conflict between the aesthetics or the architectural idea and the technical solution."[19] The first is the problem of differential thermal expansion. The structure on the outside is exposed to wide variations in temperature and the structure on the interior is exposed to much more modest variations of temperature; however, the concrete slab inside the building must be connected to the structure on the inside, the structure on the inside must connect to the structure on the outside, and the building is 220 meters long (thermal expansion is a function of length). To understand this problem: imagine a very hot day, and over the course of the day, all the exposed steel members on the outside of the building get hotter, and thus longer, pushing against each other. The movement will never be uniform and all these structural members are attached to other elements in the building. This movement can cause unsafe stresses to build up in both structural and nonstructural elements of the building and could cause problems such as cracking in the concrete slabs and shattering of glass, if not failure of the exposed steel elements themselves.

The solution to this problem is to fix the interior steel members (transverse floor girders) to the vertical members of the exoskeleton and let the horizontal elements in the exoskeleton slide horizontally, making them decorative and redundant structurally.

This solution would not have worked for the portion of the building that would bridge over the tracks. A solution that was initially proposed was to use a cable system that would make the structure effectively a suspension bridge with the weight of five spanning floors hanging from the cable in tension with the consequential horizontal reactions at the top of the cables carried as compression in the concrete slab. This option did not appeal to the architects in part because this scheme would mean the horizontal elements in the steel exoskeleton were still redundant and effectively decoration. The final design that was chosen uses a truss system where the horizontal elements of the exoskeleton are load-carrying chords of the truss. As a consequence the connections between the exterior and interior steel members are specially designed sliding connections. Such connections, however, are not optimal at transferring the load and would never be the engineer's first choice. The engineers and architects discussed the problem back and forth, but eventually the engineers found a way to make the architect's vision work, using carefully the designed connections. Schober describes the final compromise as "a distinguished design, but from the engineer's point of view, the structure is not optimal."[20]

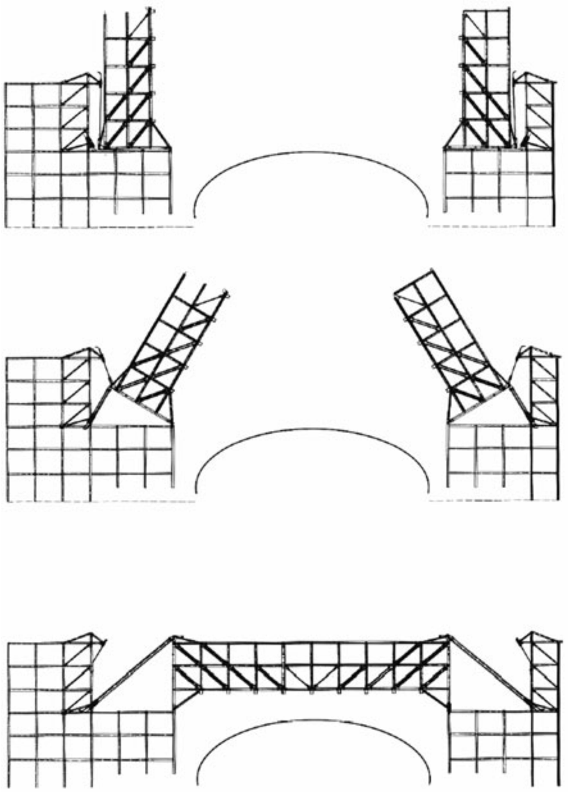


4.7a and b Structural options for the bridge portion of the office building at the Berlin Hauptbahnhof. von Gerkan, Marg und Partner and Schlaich Bergermann und Partner, Berlin, Germany, 2006.

© Schlaich Bergermann und Partner.

The final design proved to be the best solution to construct this part of the office building that would bridge over the train tracks. The truss was built vertically in two halves and rotated into place, neatly solving a construction issue at the same time. For the entrance façade walls at either end of the north–south axis the architect wanted maximum transparency. Schober initially proposed a cable net wall, where a grid of pre-stressed cables are pulled to maximum tautness allowing them to then carry the wind load and weight of glass panes in a singular sheet of structure and enclosure at once, but the architect rejected this idea as too minimal and the engineers worked on alternate ideas for the very large wall. Various proposals, including beams, beams and cables, cable trusses with diagonals, and so on were considered but the final solution was an assembly of criss-cross cables held apart from a pair of straight cables by glass fins to give structural depth and create a series of vertical Vierendeel trusses that lend stiffness to the wall against loads perpendicular to the wall (primarily wind).

The architect really wanted to use glass for the struts to maximize transparency, which an engineer might have avoided due to the brittle structural nature of glass, a particular issue



4.8 The truss bridge portion of office building at the Berlin Hauptbahnhof, under construction and lowered into place. von Gerkan, Marg und Partner and Schlaich Bergermann und Partner, Berlin, Germany, 2006.

© Schlaich Bergermann und Partner.

in a train station with the potential for vibration and vandalism. However, SBP conducted a series of tests and calculations, building prototypes and making models to design the fins, which are a laminated sandwich of four or five layers of glass with pvb interlayer. They also had to check how the wall might behave if one or more of the fins failed. Schober was very pleased with the result, which looks interesting and shows the flow of forces. Though it is not what he might have done without the architect's rejection of the initial idea, he acknowledges that the final result is better for the collaboration:

> Of course our philosophy is that if you do a minimal structure and you show the flow of forces you cannot do it wrong, but it is not necessarily the best solution from an aesthetic point of view.[21]

In this vein, Schober is quick to point out that engineers must avoid thinking there is only one solution to a design problem:

> Some engineers might be happy if they find one solution that works, our experience that there are a lot of solutions—not only one economic or efficient optimum solution . . . We have to train our young engineers to know this.

4.9 The glass façade wall. von Gerkan, Marg und Partner and Schlaich Bergermann und Partner, Berlin, Germany, 2006.

© Marcus Bredt.

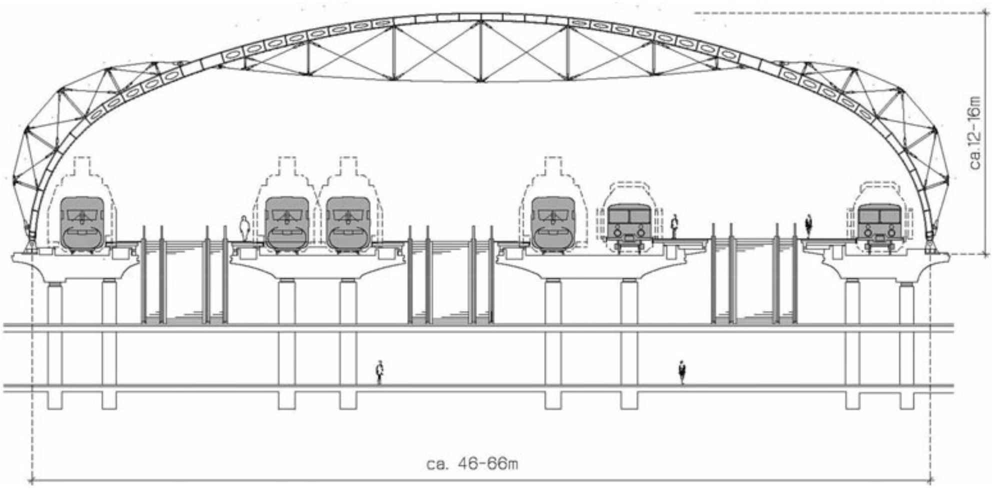
The final design for the glass wall had the added benefit of less deflection than a simple cable net would have. In this case, the architects' needs ultimately gave the engineers an opportunity to come up with another structural solution that had advantages of its own. Hilmer too, notes that shared respect and willingness to see the other's point of view is crucial in a long, large-scale project like this one:

> Particularly important is the mutual support concerning the coordination in very long projects, that means projects that span several years, and in this particular case in regards to the glass roofs and the bridge-like office buildings. The longstanding mutual understanding and trust proved to be immensely helpful in the search for acceptable and sustainable solutions to meet the various interests.[22]

The curved glass roof, which spans over five rail lines, appears to be only 13cm thick at the steel mullion that runs around the glass panes. To achieve this extraordinary thinness, the roof is supported at intervals by trusses. For this roof, the architect had specified the shape of the curve (a flatter arch than the engineers might have chosen) and that they wanted as much transparency and light as possible. So the engineers set out to design as minimal and as filigree a structure as possible. A true parabolic arch (as in the grand tradition of major train stations such as London's Paddington Station and New York's Grand Central Terminal) would have been the ideal structure, allowing for a pure compressive arch, completely eliminating bending under dead load. However, the architect successfully argued that such a high roof was unnecessary and wasteful when the era of the steam train is so long past. So the engineers were faced with designing a very long single span with a form that would have to resist bending. In order to span such a large distance and minimize the structure, it makes most engineering sense to find a form that can put material exactly where it is needed to resist the loads (and remove it where it is not necessary). Every element of the roof structure is designed with this in mind. The final design for the roof came entirely from the engineering requirements. Schober:

> We discussed various options: a frame, a frame with a cable truss, and so on, back and forth. But if you think of the principles of light structures, it is always good if you can dissolve the structure into struts and ties that take only compression and tension, rather than building a bending member.[23]

To carry the bending, a truss was designed to separate the bending into compression and tension members (struts and ties). These trusses are rendered almost invisible by aligning the compression member with the glass plane (where a structure to hold the glass is required in any case) and using thin tension cables above and below the roof in a shape that mimics a fixed–fixed bending moment diagram due to the gravity loads.[24]



4.10 Platform roof cross-section. The truss mimics the bending moment diagram of the flattened arch under dead load. The compression member of the truss is coincident with the arch, with the tension members (thin cables) held off the arch with minimal compression struts. Every effort is made to lighten the section with the compression members hollowed out except in those places where a little extra structure is needed to resist the small amount of bending under non-uniform and lateral loads. von Gerkan, Marg und Partner and Schlaich Bergermann und Partner, Berlin, Germany, 2006.

© Schlaich Bergermann und Partner.

4.11 The platform roof spans up to 66m and the maximum depth of the compression members in the arch is only 13cm. von Gerkan, Marg und Partner and Schlaich Bergermann und Partner, Berlin, Germany, 2006.

© Marcus Bredt.

To further remove weight from the cross section (in a large structure, its own self-weight is usually the largest load) and to maximize transparency, openings were placed in the compression members in the middle of the section where the material is least necessary to resist buckling. These openings are absent only at the supports and at the point of inflection of the bending moment diagram due to the dead (gravity) load. There is a small amount of bending due to wind load, which is largest at the point of inflection, and thus the compression struts that must act as beams in those locations need to be deepened slightly and the web filled back in for resistance to bending. This form, Schober argues, comes from the engineering imagination:

> This is a good example of a high-tech structure that comes mainly from the engineer, because it has only one function, to carry the load, and when this is the case the engineer should be the leading designer and not the architect. Of course the flat form came from the architect—otherwise we might have a different roof.[25]

So, while the engineer might never have started from the form of the non-parabolic arch with its attendant bending, the architect would not have come up with the details of the undulating truss form.[26] Working in collaboration, however, they produced a novel and successful design. In summing up gmp's successful collaboration with SBP, Hilmer argues that the two firms' common design values were the key to the positive outcomes:

> The most significant aspect of a successful collaboration between architects and engineers is not who assumes the leading role in regards to formal and aesthetic decisions, but rather the congruence not only in the approach to the design but also in the fundamentals of design work. Good design is dependent on a give-and-take basis. On the one hand it requires a fine balance of construction ideas and decisions in regards to fabrication and erection as well as architectural and aesthetic considerations. All considerations must be sufficiently addressed without questioning who is responsible for the one or the other aspect. The design process is solely directed at creating a coherent and comprehensive building. This is dependent on a common philosophy of design. The philosophy includes the efficient use of materials, the simple recognition of the path of structural loads, simplicity in regards to a minimalistic and honest structure and the honesty to show how a structure is connected and how it works, which together provide for an outstanding design and construction like the Berlin Central Station.[27]

Notes

1 Alan Holgate, *The Art of Structural Engineering: The Work of Jörg Schlaich and his Team*, Stuttgart/London: Axel Mengels, 1997.

2 Nina Rappaport, "Schlaich, Bergermann und Partner," in *Support and Resist: Structural Engineers and Design Innovation*, New York: Monacelli Press, 2007, p. 181.

3 J. Schlaich and R. Bergermann, *Leicht Weit/Light Structures*, Exhibition catalog, Deutsches Architektur Museum, Frankfurt Am Main, Munich: Prestel, 2003.

4 Rappaport, *Support and Resist*, p. 179.

5 Holgate, *The Art of Structural Engineering.*

6 Note this is the firm's preferred usage.

7 Volkwin Marg, "Immer hart trainieren," *Build*, Mai/Juni (2003): 15.

8 Eva Barkhofen, "Bauten für die Sinne, 40 Jahre gmp in Berlin," in *Berliner Bauten und Projekte, 1965–2005*, Berlin: Jovis, 2005, pp. 9–10.

9 "Practice Profile," gmp Architekten von Gerkan, Marg und Partner, http://www.gmp-architekten.com/projects.html (accessed July 29, 2013).

10 Meinhard von Gerkan, "Editorial," in *Von Gerkan, Marg and Partner: Architecture 1999–2000*, Basel: Birkhäuser, 2002, p. 8.

11 "Philosophy," gmp Architekten von Gerkan, Marg und Partner, http://www.gmp-architekten.com/projects.html (accessed July 29, 2013).

12 "Projects," gmp Architekten von Gerkan, Marg und Partner, http://www.gmp-architekten.com/projects.html (accessed July 29, 2013).

13 "Die Bahnhofe," Deutsche Bahn, http://www.bahnhof.de/?lang=en#station/17620 (accessed July 29, 2013).

14 Eva Barkhofen, "Berlin Hauptbahnhof – Lehrter Bahnhof, 2006," in *Berliner Bauten und Projekte, 1965–2005*, Berlin: Jovis, 2005, p. 144.

15 Rappaport, *Support and Resist*, p. 184.

16 Hans Schober, Interview by authors, personal interview, Stuttgart, June 19, 2013.

17 Ibid.

18 Jürgen Hilmer, Interview by authors, email interview, Hamburg, August 2, 2013.

19 Schober, Interview.

20 Ibid.

21 Ibid.

22 Hilmer, Interview.

23 Schober, Interview.

24 Hans Schober, "The Berlin Connection," *Civil Engineering*, 81 (2006): 43–89.

25 Schober, Interview.

26 Ibid.

27 Hilmer, Interview.

– 5 –

B2 BKLYN

Owner Developer	Forest City Ratner Companies
Architect of Record	SHoP Architects
Structural and Mechanical Engineer	Arup
Integrator	SC (SHoP Construction)
Modular Consultant	XSite Modular
Construction Manager	Skanska
Modular Contractor	FC + Skanska Modular, LLC

ALTHOUGH multiple experts worked together on the design of B2 BKLYN, the case study focuses on the collaboration of Arup, SHoP Architects and SC. We begin with the background on the firms.

Arup

OVE Arup, one of the world's most prominent civil engineers, founded Arup Group as a structural engineering firm in 1946. The firm rapidly developed a reputation for innovative approaches to resolving structurally challenging designs. One of the first triumphs for the firm was the engineering design of the Sydney Opera House. Jørn Uzton's competition-winning design was groundbreaking formally, but extremely difficult to resolve technically due to its complex geometry; in fact it was initially rejected by the technical panel for the competition. However, with the research, investigations in complex geometries, and innovative material use that remain hallmarks of the firm's work to this day, the project was successfully completed.

Ove Arup was recognized as a visionary leader in the field and he wrote and lectured extensively about the value of structure to the architectural design process: "Great architecture can be created from a tortuous structure or at an inordinate cost, but it would be greater still if structural clarity and ease of construction could be added to its virtues."[1] When describing the collaborative process of engineers and architects he said that integrated teams should learn about one another's disciplines to become more successful collaborators, and the best way to do this is to actually collaborate.[2]

The success of the firm enabled rapid expansion and today close to 100 offices throughout the world employ over 11,000 people in a wide range of disciplines. The core mission of the firm was described in an address called the "Key Speech" given by Ove Arup to partners gathered at a meeting in 1970 that remains a touchstone for the firm's practice. Ove described the need for employees—who are also owners of the firm—to work closely together, especially as the firm expands. Ove reminded them of his vision for the firm's mission:

> In our work as structural engineers we had—and have—to satisfy the criteria for a sound, lasting and economical structure. We add to that the claim that it should be pleasing aesthetically, for without that quality it doesn't really give satisfaction to us or to others.

It is this philosophy that has made Arup one of the most revered engineering practices in the world, enlisted for design collaborations by prominent architects and clients on high-profile projects.

In recent years the firm has contributed to the design of The National Aquatics Center (The Watercube) designed with PTW Architects, the National Stadium (Bird's Nest) with architects Herzog and De Meuron for the Beijing Olympics, 30 St. Mary's Axe ("The Gherkin") with Norman Foster, the CCTV Headquarters in China and the Seattle Public Library, both with Rem Koolhaas. The firm continues to have a strong reputation for research and innovation leading to creative solutions for boundary-pushing structures.

SHoP Architects and SC

SHoP Architects, founded in 1996 by partners Christopher Sharples, Coren Sharples, William Sharples, Kimberly Holden, and Gregg Pasquarelli, has since grown to include partners Jonathan Mallie (2007) and Vishaan Chakrabarti (2012) and support a staff of over 120 designers, project managers, innovators, and architects. Since the firm's conception, the partners continue to question normative standards of the profession of architecture, defining a more humanist approach, where innovation is promoted at all levels of practice including design, drawings, working methods and construction.

Core innovation is central to SHoP's mission to redefine the design practice. The office invests in research, software development and human resources to facilitate construction of cutting-edge design work. Technology research and construction innovations are demonstrated in the seminal Porter House (2003), clad in digitally fabricated zinc panels, and the Camera

Obscura project (2005) in which the architects took a groundbreaking and highly influential approach to construction documents and shop drawings. Each of the building's 750 components was fabricated using computer numerically controlled (CNC) machines and arrived on site as a kit-of-parts. With each piece pre-cut, this enabled an assembly process that negated traditional construction documents.

Innovation is also central to SHoP's business model. The partners have started three companies, including a sister company SC in 2007, which offers services in areas such as management of Building and Information Models including coordination of various systems locations in what is known as clash detection, and the development of Virtual Design and Construction (VDC) packages and construction management. By creating their own solutions, developing and harnessing emerging software, they are demanding a new set of tools to innovate

5.1 SHoP Architects, Arup, B2 BKLYN, Brooklyn, New York, 2014.

© SHoP Architects.

and collaborate, leading rather than following in a realm that has traditionally been slow to change. SHoP Architects and SC are trailblazing a unique and award-winning approach to the profession of architecture, garnering a snowballing array of commissions at increasingly larger scales.

SHoP Architects is designing the skyline of New York at a rapid pace, prompting journalist Jason Sheftell to state that, "In 12 years, SHoP has shaped more of 21st-century New York than any single architectural group might do in the next 100."[3] Projects include the master plan of the Williamsburg waterfront for the $1.5 billion Domino Development, a mixed-use complex with 925 affordable housing units on the Queens waterfront at Hunters Point South, and the Atlantic Yards development in downtown Brooklyn, which is the focus of the following case study.

Introduction to the Project

Although it may be unfair to use superlatives in a text such as this one, the B2 BKLYN residential tower, also called B2 Modular, may be one of the most truly collaborative projects in the world to date. Not only were the architects, engineers and contractors organized to work as a team from the start of the project, but the inventiveness required for this new building type made working collaboratively essential. The story of the building's realization is one where the integration of a multidisciplinary team is so fundamental to the process that it enabled innovation in every detail of the project.

The B2 BKLYN residential tower is part of Atlantic Yards, a 22-acre development comprising 14 buildings in the heart of Brooklyn by one of New York City's most prominent developers, Forest City Ratner Companies (FCRC), a subsidiary of Forest City Ratner Enterprises, Inc. The developer has championed some of the most significant projects in New York City in recent years, including the New York Times building designed by Renzo Piano Building Workshop in association with FXFowle Architects and the tallest residential tower in the city, New York, located at 8 Spruce Street, which is the first completed New York residential commission designed by Gehry Partners.

Atlantic Yards is an extremely ambitious, mixed-use development that includes residential towers that provide 6 million square feet of affordable and market-rate housing. It also includes the Barclays Center Arena, home to the Brooklyn Nets and New York Islanders, as well as 247,000 square feet of retail space, an additional 336,000 square feet of office space, and about 350,000 square feet of public outdoor space.

Gehry Partners conceived the Atlantic Yards master plan over a six-year period. The firm was slated to design the first phase of the development, the arena, but the project was eventually handed over to SHoP Architects, who designed and completed the award-winning stadium by the fall of 2012. After the Barclays Arena, the second phase of construction includes one of three planned residential towers; all three towers are designed as prefabricated modular steel

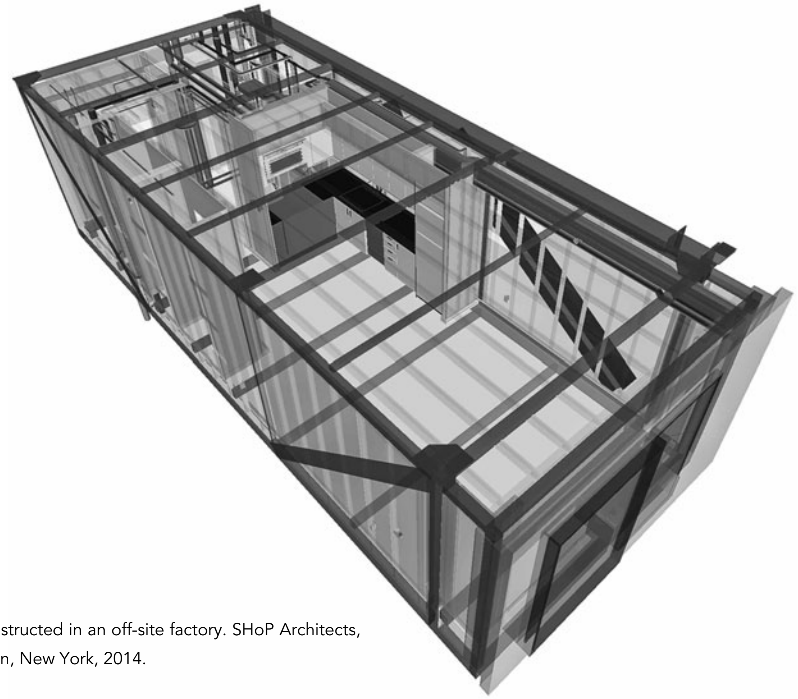
5.2 The B2 BKLYN Tower is to be a part of the Atlantic yards, alongside the Barclays Center. SHoP Architects, Arup, B2 BKLYN, Brooklyn, New York, 2014.

© SHoP Architects.

structures with 60 percent of the construction scheduled for off-site construction, which is anticipated to save up to 20 percent of costs over conventional construction.

Although B2 BKLYN has already received worldwide recognition for innovations in prefabrication, the towers were originally designed to be conventionally constructed. FCRC hired two multidisciplinary teams concurrently, one working on a conventional tower and one investigating prefabrication, enabling the developers to thoroughly compare apples to oranges and assess costs. It's not surprising that prefabrication came out ahead. In a 2011 McGraw Hill Report, *Prefabrication and Modularization: Increasing Productivity in the Construction Industry*, 65 percent or more of the 800 architects, engineers and contractors surveyed reported that project schedules, budgets and site waste all decreased when using off-site construction. Given the planned number of units, building height and site conditions, prefabrication provided a compelling opportunity for significant cost savings as well as numerous environmental and community benefits.

It also didn't hurt that during design development of B2 BKLYN, Broad Group completed a 30-story modular five-star hotel, T30 in Beijing, constructed in just 15 days, proving that a building of a comparable height could be completed in record time. This helped to motivate a full commitment to prefabrication, and the design team dedicated their focus on



5.3 930 units will be constructed in an off-site factory. SHoP Architects, Arup, B2 BKLYN, Brooklyn, New York, 2014.
© SC.

the development of the modular system. "The developer, Forest City, played the major role in all this—their vision for undertaking modular construction was really pretty extraordinary. Having a great client like that who is willing to take the right steps to make a project like this possible is not to be underestimated,"[4] said Alex Terzich, Design Associate and Façade Specialist with SHoP Architects.

At 32 stories, B2 BKLYN is slated to be the tallest modular tower in the world (at the time of writing). There will be 363 living units (50 percent low to middle income and 50 percent market rate), and the building will be composed of 930 modular units. About a third of these, or 227 to be exact, are unique structural types. Each module ranges from 10–15 feet wide and 20–50 feet long. Construction on B2 BKLYN began in December 2012 and each additional building that is part of the multi-use complex, including two more residential towers, is scheduled to start construction in sequential nine-month intervals.

Although prefabrication is not new for New York City, the scale of the endeavor was not without controversy. Labor unions complained that the modular structure meant a reduction in on-site union jobs since the majority of the construction jobs would be shifted to the factory in the Brooklyn Navy Yard, which is also unionized. After numerous public hearings and permitting processes, the inevitable economic and cultural benefits of the development triumphed and the project received the go-ahead to break ground. In a *New York Times* article, "Prefab Lives!," Gregg Pasquarelli was quoted as saying, "We believe a modular approach to high-rise housing will lead to a better quality of life for communities living near and around modular-based building sites . . . Modular construction offers the possibility of safer sites and better-manufactured buildings at standard construction costs. It's a win-win proposition."[5] The benefits are abundant, and because of the remarkable reduction in waste and energy use during the construction process, B2 BKLYN is on track to obtain a LEED Silver certification by the U.S. Green Building Council.

The Collaborative Design Process

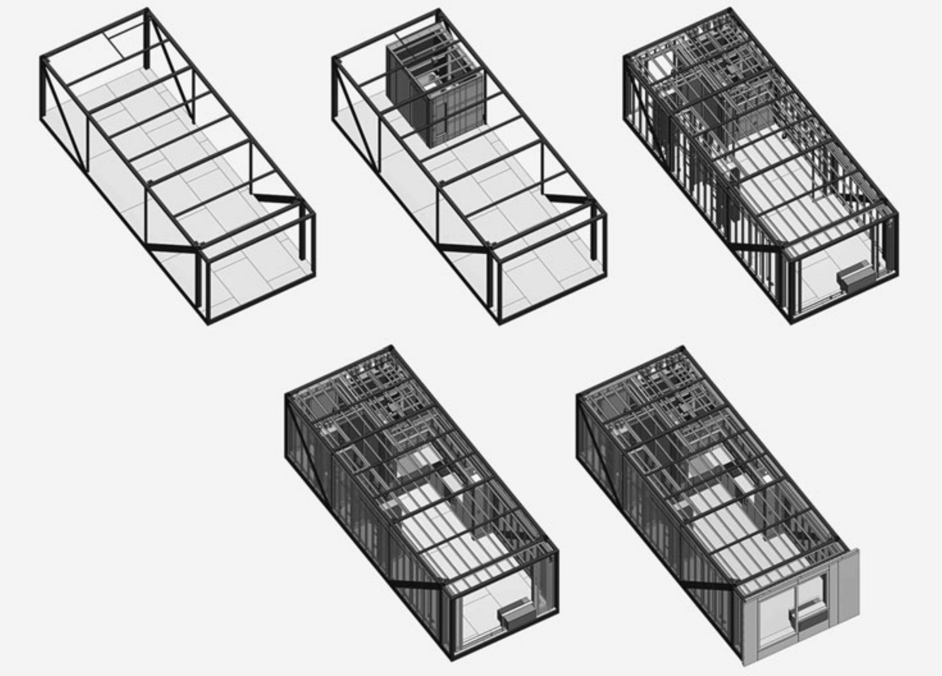
The initial integrated project team included Arup for structural/mechanical-electrical-plumbing (MEP) / acoustic consulting / fire life safety consulting, SHoP Architects, SC, FCRC and X-Site (the modular consultant on the team that worked early on to test fabrication ideas through preconstruction). It is an understatement to say that B2 BKLYN is complex. Erik Churchill with SC oversaw project integration and described the necessity of the interdisciplinary team:

> One of the things that was very challenging about this design process was that in many ways it is the reverse of a traditional design process. In the traditional design process, you work from the macro to the micro and get more and more specific with the problems you're solving. But in many ways, such as how to connect the "mods" [modular units] from MEP to carpentry to structure, all had to be resolved at a very detailed level very early. So it was a challenge to the team to be dealing with a scale that was hyper specific from the beginning of the project. The whole process was a learning curve and that's why the conversations of the integrated team became so important, because you were working with fabricators and engineers to integrate details into the base geometry.[6]

The structural framework served as the basis for developing the design and systems. The initial feasibility study by Arup determined that B2 BKLYN should be an all steel structure. David Farnsworth, Arup Principal in charge of structural design, describes the two systems at work: (1) individual steel modules that are stacked on top of one another to handle gravity loads; and (2) a braced frame system to deal with lateral wind loads, which is critical to the design of tall structures. Each module (or "mod") has its own structure with diagonal straps for bracing that add strength and efficiency, but also create obstructions in the mods that needed to be integrated into the design concept. Farnsworth states that, "The B2 Modular project represents collaboration at the highest level, which is filtered down into every detail."[7] The team discussed the design of systems on a daily basis and the logistics and details were coordinated using a robust Building Information Model (BIM) in Revit. "Because the goal was to finish all the modules off site, each module needed to be designed holistically utilizing BIM to ensure very tight, coordinated locations for the structure and infrastructure of each mod."[8]

This points to one of the design drivers for the project. As Terzich describes, the most important rule of prefabricated construction is maximizing the factory and minimizing the field, so the architects, engineers and fabricators worked together to develop a wide range of prefabricated components. Terzich describes the prefab units as including "large-scale modular frames, prefabricated façade panels, bathroom units, mechanical system, pre-cut materials, and so forth."[9] The goal to condense the on-site construction led to a number of creative solutions. Often in modular construction, the units are welded from the interior and the finishes are applied on site. With three people required to weld (the welder, fire watch and machine holder) the process is complicated and costly, so the aim was to minimize welding as much as possible. This spurred one of the most innovative aspects of the project from a structural and construction perspective: instead of welding the mods from the inside, Arup worked to develop a strategy for bolting the modules together from the outside of the apartment units, which meant that each unit could be finished in the factory right down to the hardwood floors.

Given the construction strategy for B2 BKLYN, there is no need for extensive scaffolding on site, which would have been challenging and costly in the urban context. Instead, says Farnsworth, a tower crane with a 53,000 pound capacity within a radius of 75 feet will be fixed on site to lift each of the 900-plus modules into place. The crane's capacity, which was known



5.4 Each module will be constructed in an off-site factory. The steps are illustrated above: Step 1 Structural Steel, Step 2 Pod Assembly, Step 3 Framing/MEP, Step 4 Gypsum/Kitchen, Step 5 Finishes/Façade. SHoP Architects, Arup, B2 BKLYN, Brooklyn, New York, 2014.
© SC.

early in the design process, placed weight parameters on the project, and became a design constraint. Because of the minimal scaffolding, the design team developed a strategy for applying the façade finishes in the factory, which is not typical for stacked prefabricated construction. Terzich worked to

> resolve some of these challenging issues of how to prefabricate a façade system that is coming along for the ride on a 40,000 pound module . . . In this case, we were trying to solve the problem of how to get the façade to seal up and achieve the performance of a typical high-rise curtain wall, but without the tolerance precision that you would get in a conventionally-set system.[10]

He describes a concerted research process that included discussions with numerous manufacturers and fabricators. The team collaborated on the design of an over-cladding system of lightweight, durable foam and finishes, and a proprietary gasket system connects the gaps between modules.

The connection between modules, referred to as the mateline, was another driver of innovation for B2 BKLYN. Modular construction results in additional floor and wall build-ups due to fireproofing and constructability criteria. In an effort to create the highest possible floor plan efficiency, each build-up was reduced as much as possible. For B2 BKLYN, the design team worked to reduce the boundary thicknesses, but this meant that structure and MEP needed to be very efficiently packed. That kind of integration could not have occurred without an extremely detailed and finely tuned cloud-based BIM model. With the structure and MEP compressed to make the matelines thinner, the multidisciplinary team needed to work very closely to design an efficient, cohesive digital model, essentially constructing the building virtually, in order to avoid conflicts in the field, a time-consuming and challenging prospect.

The team from SC, led by Erik Churchill, used a variety of software to manage the integrated project, including Revit and BIM 360 for reviewing the project in order to integrate the construction sequence and methods into the design. Churchill also managed and monitored clashes in the shared BIM model. From Revit to GoToMeeting software, communication proved pivotal to the process. The integrated team consulted one another multiple times per day, relying on each individual's expertise to innovate new design strategies and insure coordination. Cost and efficiency drove much of the decision-making, according to Farnsworth: "Contractors, architects and engineers were continually working on cost feedback; design decisions were often driven by production considerations (for example, whether something would take 10 hours to install or 16 hours). These goals helped to refine the design work."[11] Although the research and design process consumed more time than it would have on a conventional project, the front-ended approach insures an efficient construction process. With design fees being such a small percentage of overall costs, investment in research can lead to real pay-offs in material and construction efficiency.

In the case of B2 BKLYN, the collaborative mode was based on respect and interdependence— each team member was valued and crucial. Fundamentally, Churchill remarks that

5.5 B2 BKLYN would not have been possible without the close collaboration of a multidisciplinary team. SHoP Architects, Arup, B2 BKLYN, Brooklyn, New York, 2014.

© SHoP Architects.

integrated project delivery "is all about the structure of communication and personalities."[12] Farnsworth agrees, adding that, "In today's working environment, one needs to be able to collaborate, be quick to get on the right side of a job, have a willingness to take responsibility, but also know when to share credit."[13] Each person interviewed about the project recognized that B2 BKLYN would not have been possible without the full-hearted collaboration of an integrated, multidisciplinary team from the start of the project. Terzich concludes, saying, "Ultimately as a team we worked together to make sure everything came together in a cohesive whole. Collaboration was a necessity—there really wasn't much of a choice, but we did enjoy it!"[14]

Notes

1 Ove Arup, “Architects, Engineers and Builders,” The Alfred Bossom Lecture to the Royal Society of the Arts, London, March 11, 1970.

2 Ove Arup, “The Architect and the Engineer,” *ICE Proceedings*, 13(4) (1959).

3 Jason Sheftell, “Domino delivers! Master plan at former sugar refinery brings park land and hopefully high-tech jobs to Brooklyn,” *Daily News*, March 15, 2013, nydailynews.com.

4 Alex Terzich, Interview by authors, phone interview, New York, NY, May 2, 2013.

5 Allison Arieff, “Prefab Lives!” in The Opinion Pages, opinionator.blogs.nytimes.com/2013/05/23/prefab-lives/.

6 Erik Churchill, Interview by authors, phone interview, New York, NY, May 2, 2013.

7 David Farnsworth, Interview by authors, phone interview, New York, NY, June 4, 2013.

8 Ibid.

9 Terzich, Interview.

10 Ibid.

11 Farnsworth, Interview.

12 Churchill, Interview.

13 Farnsworth, Interview.

14 Terzich, Interview.

Toledo Museum of Art Glass Pavilion

Client	Toledo Museum of Art
Architect	SANAA Kazuyo Sejima + Ryue Nishizawa
Design Team	Toshihiro Oki, Takayuki Hasegawa, Keiko Uchiyama, Mizuki Imamura, Tetsuo Kondo, Junya Ishigami, Florian Idenburg
Structure	Sasaki and Partners & Guy Nordenson and Associates
Glass Consultant	Front Inc.
Lighting	ARUP/Kilt Planning

THE Toledo Museum of Art Glass Pavilion was a collaboration that encompassed many individuals and companies. This case study will focus on the collaboration among SAANA, Sasaki and Partners, and Guy Nordenson and Associates.

SANAA

SANAA, Sejima and Nishizawa and Associates, is a Japanese architecture firm founded by Kazuyo Sejima and Ryue Nishizawa in 1995. Their large and highly lauded body of work demonstrates a refined approach to lightness and transparency through a subtle use of structure and materials. Their designs often involve open, democratic plans with a blurred boundary between exterior and interior, and a relationship with the surrounding natural environment.[1] The practice rose to international prominence with the design for the 21st Century Museum of Contemporary Art in Kanazawa Japan, the Prada Store in Arezzo Italy, and their Gifu Kitagata Apartment building. Significant recent works include the extraordinary rolling shell structure for the Rolex Learning Center in Lausanne, Switzerland, a dynamic stack of subtly radiant shifting boxes for the New Museum of Contemporary Art in New York City, a satellite museum for the Louvre in the French city of Lens, and an impossibly thin reflective metallic roof supported on the thinnest of columns for the Serpentine Pavilion in Hyde Park, London.

Nishizawa describes their approach to design as:

> Coherent, consistent, always doing the same thing. One of our constant big concerns is how to create a relation between the inside and outside, this is very important for us to think about.[2]

Sejima adds:

> Probably our interest now is more how to organize "a program" within a building—the layout of rooms and how people move inside. But also how to keep a relationship between the "program" and the outside and then how the outside fits to the surroundings. In each project we have different requirements and the site is different, we try to find our way.[3]

They jointly won the Pritzker Prize (architecture's highest honor) in 2010. In awarding the prize, the jury praised them for:

> Architecture that is simultaneously delicate and powerful, precise and fluid, ingenious but not overly or overtly clever; . . . creation of buildings that successfully interact with their contexts and the activities they contain, creating a sense of fullness and experiential richness; for a singular architectural language that springs from a collaborative process that is both unique and inspirational.[4]

Sasaki and Partners (SAP)

MUTSURO Sasaki, a Structural Engineer based in Tokyo, has worked closely on numerous projects with SANAA and with other prominent Japanese architects such as Toyo Ito. He studied both architecture and engineering at Nagoya University and went on to receive a PhD in structural engineering. His particular expertise is in resolving complex geometrical forms. To this end his research as professor at Tokyo's Hosei University has led to the development of computational optimization techniques to facilitate form generation that maximizes efficiency of non-regular structural forms and systems.[5, 6]

Increasingly, these methods allow for resolving the structure of three-dimensional surfaces that are free and organic, opening up architectural potential and pushing the limits of engineering.[7] For example, at the Kakamigahara Crematorium designed in collaboration with Toyo Ito in 2006, he used a method called sensitivity analysis to design a free-form concrete shell roof sitting on 12 columns and four bearing walls. Traditionally to minimize bending in a concrete shell (and thus avoid a deep, ungainly, and uneconomical cross section), the form must be designed from a series of known optimal forms, or derived from a funicular model where a hanging form in tension is inverted to find a form that will only have compression, as in the work of Antoni Gaudí or Heinz Isler. Sensitivity analysis is an iterative computer design methodology that bypasses the conventional sequential process and finds directly the optimum structural form that satisfies given design parameters. Starting with an envelope idea of where the roof will be and some other formal constraints for the roof design, the sensitivity method optimizes the exact shape of the roof by continually recalculating the strain energy at a matrix of nodes on the roof and varying the height of the roof in the direction that will minimize that strain energy. Sasaki claims that shape analysis effectively replaces Gaudí's physical experimental method of the hanging model with a modern theoretical method.[8, 9] These innovative methodologies are key to the collaborative nature of his work. "This type of multi-objective optimization enables designers and engineers to collaborate in clear and robust frameworks, provides common basis for the cross-disciplinary teams to make more informed decisions, and fosters the culture of creativity and innovations."[10] Sasaki has an especially collaborative relationship with his architecture colleagues and works very closely with them in the initial design phases of a project:

> It is always like this, whether with a competition when the elements are not defined, or with a particular project; when the architect has an idea, we have a discussion directly. All of the ideas of the projects have to be discussed from the structural standpoint because the idea of the structural engineering influences the design itself.[11]

The value he places on the equality of both the architectural and engineering point of view in the process of developing a structural system is also clear: "The structural engineer's role is thereby defined as being more like an architect than an engineer . . . They must undertake their collaborations from an equivalent standing."[12] He also notes that collaborative relationships are a function of the relative positions of the collaborators in their careers and fields and that he has both learned a great deal from his primary collaborators and in turn been a teacher at times:

> I have maintained long-term collaborations with some of the most influential architects [to me], and especially Arata Isozaki, Toyo Ito, and SANAA/Sejima and Nishizawa have had strong influence on my career. My relationships with each of them are different, my responsibility for them and with them are different. In the case with SANAA, when we started our collaboration, I was in my 40s while they were at their 30s and 20s. Therefore, my role with SANAA has been more as a mentor to lead our collaboration. This is how we pass down the values, knowledge, and wisdom from one generation to the next.[13]

Guy Nordenson and Associates

Guy Nordenson is a structural engineer practicing in New York City, who works closely with a number of prominent architects. His firm is described in more detail in Chapter 8 where the Simmons Hall project designed by architect Stephen Holl (for which his firm served as structural designers) is discussed. Guy Nordenson Associates were consulting engineers in the United States for the Toledo Art Museum Glass Pavilion in collaboration with Sasaki and were critical to the processes of structural design development, construction documentation, local permitting, code compliance, and construction administration.

The Project

Toledo, in northwestern Ohio, grew rapidly in the latter part of the nineteenth century with the building of the Erie Canal and the New York to Chicago rail lines, becoming an industrial center with a number of manufacturing specialties, among them glass-making. The Glass Pavilion of the Toledo Art Museum was built to house the impressive collection of contemporary and historical glass art amassed by the museum, which was founded by the President of the Libby Glass Company.[14] The site for the building is situated among a campus of buildings that includes the original Beaux Arts museum building completed in 1912 and the Center for the Visual Arts, a Frank Gehry project completed in the 1990s. The museum did not hold a competition to find a designer; instead they hired SANAA directly to design the project. Some may have viewed this as a risky move since the firm was relatively unknown in the US at the time, but that risk has certainly paid off. The final project has received much praise from the architectural press, and SANAA has gone on to design a number of prominent and highly regarded projects in the United States and internationally.

Described by Michael Webb in *Architectural Review* as a "delicate crystal casket for a major collection of glassware,"[15] the pavilion was designed to house galleries and courtyards on the ground level, along with two glass-making studios used by the art department at the University of Toledo. The low horizontal building is perfectly rectangular in plan, measuring 187 feet by 203 feet, and sits amid grass and trees on a large town-square-like lot.[16]

In their design for the Glass Pavilion, Sejima and Nishizawa create dramatic tension seemingly out of the air, using the thinnest, most minimal, and most transparent elements of structure and enclosure.[17] The pavilion appears from the outside as a stripe of white roof sitting atop a band of glass. Inside, most interior walls are glass with curved corners. Low-iron glass panels, 8 feet wide and 13½ feet high, and up to one inch thick, make up the transparent walls.[18] Iron is what gives glass a greenish hue, so this low iron glass has greater clarity. The 35 thin columns (some as slender as 3½ inches in diameter[19]) that support the structure recede from view behind the glass or are hidden in the few sections of opaque walls, contributing to the illusion that the roof floats above the glass walls.

6.1 SANAA & Sasaki and Partners, Glass Pavilion at the Toledo Museum of Art, Toledo, Ohio, 2007.

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6.2 SANAA & Sasaki and Partners, Glass Pavilion at the Toledo Museum of Art, Toledo, Ohio, 2007.

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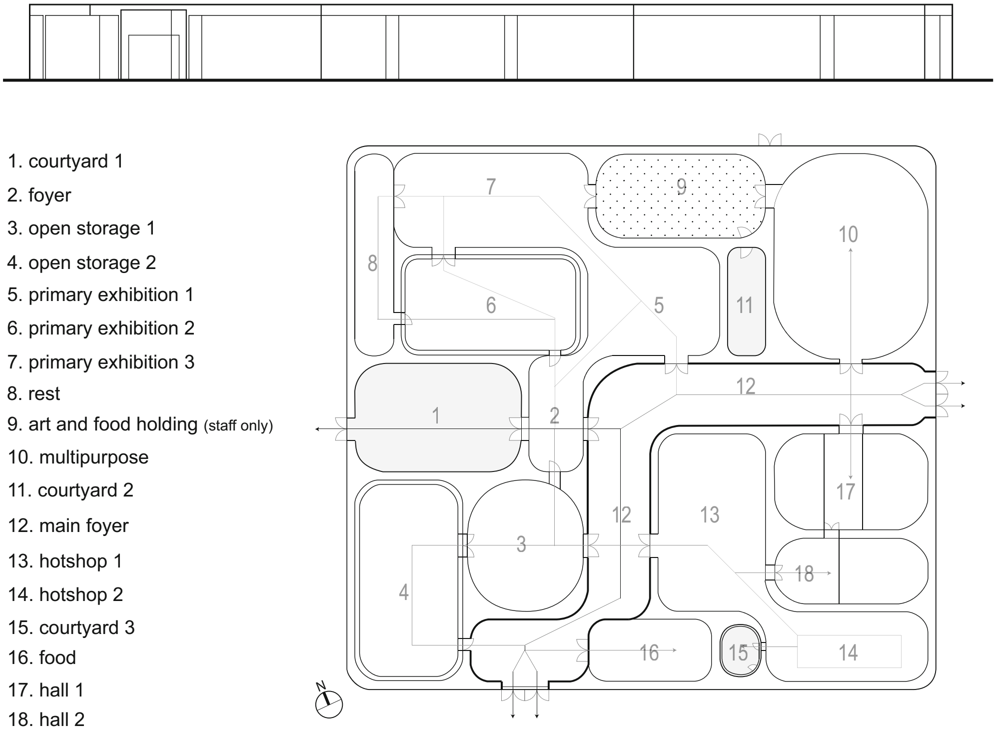
The all-glass building appears reflective and shiny by day, but at night, lit from inside, the glass disappears and the patrons and artists emerge in silhouette.[20] *New York Times* critic Nicolai Ouroussoff describes the project:

> Composed with exquisite delicacy, the pavilion's elegant maze of curved glass walls represents the latest monument to evolve in a chain extending back to the Hall of Mirrors at Versailles . . . [a] diaphanous maze. The interior is a series of rounded glass rooms wrapped in a secondary glass skin, which creates a remarkably layered visual experience . . . creating a more fluid dynamic between the art and the viewer.[21]

There are two opaque galleries, walled in to block light from works that might be damaged by such exposure, which Ouroussof argues "serve to anchor a structure visually that might otherwise seem about to drift off into space,"[22] an apt description since these walls also hide the structural braces that provide the lateral stability to the building.

At ground level, there are also three courtyard spaces open to the sky above, as shown in the plan and elevation diagrams. These serve to balance light coming from the outer perimeter



6.3 Plan and Elevation, SANAA & Sasaki and Partners, Glass Pavilion at the Toledo Museum of Art, Toledo, Ohio, 2007.

© Christina Hoover.

and minimize glare inside the building. Architectural critic Clifford Pearson argues that these spaces along with the interstitial spaces created by the curved glass walls have "a strong visual presence, but remain tantalizingly out of reach."[23] He further posits that "In Japanese architecture, the concept of ma—a gap in time or space—has long played an important role . . . [SANAA uses] ma to animate what could be considered just wasted, leftover space."[24] Nishizawa himself writes that an exploration of "separating the rooms" has long been a study that he has returned to again and again in his design work.[25] Writing specifically about the Glass Pavilion, he explains,

> Each function is positioned appropriately then wrapped in transparent curved glass to form an independent space . . . the outside connects to the inside, or the rooms in the inside connect with each other, integrating the surrounding green landscape. Here people can stroll about as one pleases, like ranging through the forests.[26]

However, he also notes that the interstitial spaces between the glass walls have additional, more prosaic functions: they serve as a buffer zone allowing the museum staff to regulate the temperature of each room separately as required. These spaces also provide sound insulation between the studio programs and between the gallery spaces.[27]

Air handling in this building is especially crucial, with glass furnaces running at 2300 degrees in the hot glass-blowing studios, while adjacent spaces might house delicate and ancient

6.4 Glass Workshop. Note that the double layer of low-iron glass is clear to provide a view from the outside in. SANAA & Sasaki and Partners, Glass Pavilion at the Toledo Museum of Art, Toledo, Ohio, 2007.

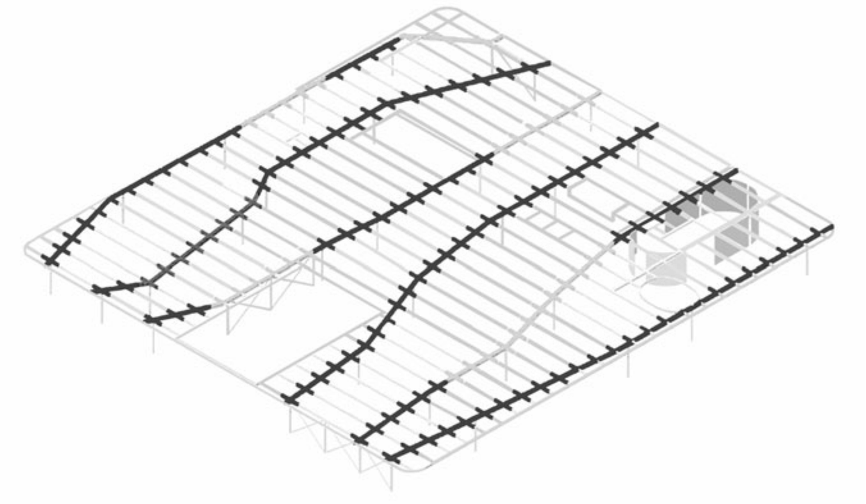
© Guy Nordenson and Associates.

art works that require a cool environment.[28] Combine these complex air-handling needs with the very shallow available cavities for ductwork in both the roof and the floor and you have a considerable logistical challenge.[29] These cavity spaces were shallow in order to minimize both the excavation depth for financial reasons and the visible thickness of the roof for aesthetic reasons. The low-slung horizontality of the building, allowing it to sit under the shady tree canopy on the site, clearly contributes to the climatic experience while creating an overall effect that is both unobtrusive and unpretentious. Additionally, neighbors objected to any mechanical equipment being visible on the roof, necessitating the conversion of a nearby building to house the HVAC systems one normally finds on the roof.[30]

Sasaki designed the structure for the building in collaboration, first with the architects and later with the American engineering team at Guy Nordenson and Associates. Architect Toshihiro Oki worked for SANAA on the Toledo project. He describes the working relationship between SANAA and Mutsuro Sasaki who have completed many projects together as a particularly collaborative one:

> He [Sasaki] is always in the office . . . at any given time when he comes in, he looks at multiple projects that could be at any different phase in the process. He's always involved in projects as an integral part from the very beginning. Everything, right from the conceptual phase . . . There is always an opportunity for people in the office to just put things in front of him and get feedback. In the US, engineers are generally hired for a specific project and you don't typically ask them about other projects, but seeing that he is part of the office, whenever he is there, people just put things in front of him. That's why I think the architecture and the engineering is so integrated from SANAA's office . . . he is not giving design direction, but based on his feedback, design shifts and changes and evolves. He's not saying "we should make a building out of this material" but if architects direct specific questions to him like, "what do you think about this column spacing or this kind of structure, can we do it out of concrete or steel?", he'll come back with some feedback that no one ever thought about . . . It's a very specific question and answer process, but based on his feedback, the design tends to evolve.[31]

In the Glass Pavilion, the structure seems simple at first glance, but it is deceptively complex. Sasaki proposed a series of different systems for the roof that had relatively long spans but had to be very shallow to align with the architect's vision for the slim, lightweight, horizontal appearance of the project. Some of the initial ideas were too costly to realize. One system initially proposed was a steel plate system similar to one he designed for the Sendai Mediatheque project with Toyo Ito.[32] This early design called for a slab-like system with a horizontal steel plate on the bottom and top with vertical ribs in between that can be customized to the particular load conditions. This was a very innovative approach to a steel spanning system that has to accommodate an irregular column grid, and it was very successful in the Mediatheque project. Unfortunately, this system proved too difficult to achieve in the United States as the volume of



6.5 Structural frame. The primary beams are highlighted; they meander back and forth with the column locations that are dictated by programmatic needs. The X braces provide lateral support as does the curved steel plate wall on the right of the diagram. SANAA & Sasaki and Partners, Glass Pavilion at the Toledo Museum of Art, Toledo, Ohio, 2007.

© Guy Nordenson and Associates.

6.6 Structural frame. SANAA & Sasakai and Partners, Glass Pavilion at the Toledo Museum of Art, Toledo, Ohio, 2007.
© Toshihiro Oki.

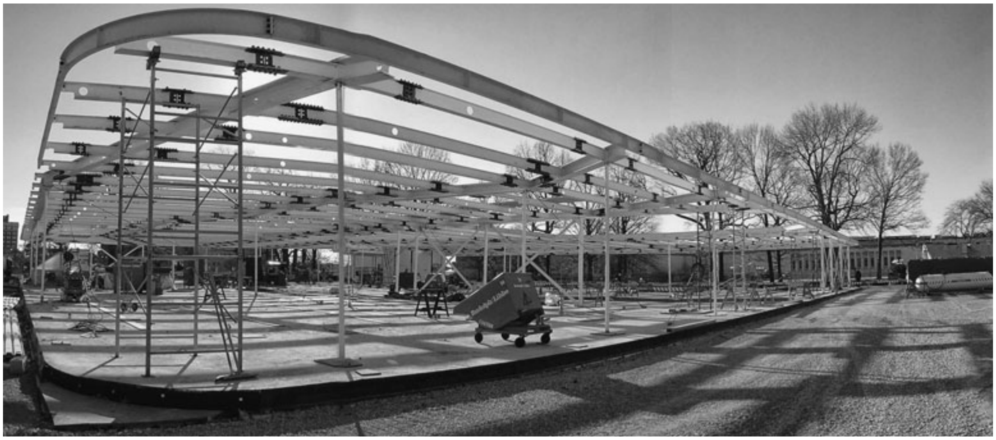
steel required made it too expensive relative to standard commercially available steel members. Ultimately, Sasaki designed a system of girders and beams.

The primary beams (girders) are not aligned to a series of straight axes through the building, as would be typical. The beams meander back and forth on a crooked line as the columns are shifted back and forth. This column placement is necessary to align with the architects' plan for the glass walls that enclose a distributed and varied set of programs. The columns also meander to align with the programs in the basement below, which shift in plan to accommodate the equipment required to move heavy pieces of art. The secondary beams run 90 degrees to the girders.

In order to keep the roof as thin as possible, the utilities were not hung below the beams and girders as is the norm in standard construction. Penetrations cut in the webs of the secondary beams were used for all the sprinkler lines, drains, and electrical cables, so everything was sandwiched in the steel layer. A system was devised where most penetrations went through the secondary beams. Only trunk line penetrations went through the girders. A careful hierarchy had to be created as it was a complex process to fit everything into the steel layer. For example, drain lines need to pitch one-eighth of an inch per foot, so when a drain penetrates a beam at

6.7 Glass installation. Note the very shallow available space between the underside of the roof deck and the underside of the ceiling where the mechanical systems had to be carefully inserted. SANAA & Sasaki and Partners, Glass Pavilion at the Toledo Museum of Art, Toledo, Ohio, 2007.

© Guy Nordenson and Associates.



6.8 Structural frame under construction. Note the notches and penetrations for the utilities. SANAA & Sasaki and Partners, Glass Pavilion at the Toledo Museum of Art, Toledo, Ohio, 2007.

© Toshihiro Oki.

a certain point on its cross section, it is passing through the next beam at lower point, and so on.[33] Cutting into the web of a beam to accommodate utilities is possible because the bending (which is the main structural concern) is largely carried in the top and bottom flanges of the beam. However, cutting a notch in the bottom of the beam is to be avoided, as is cutting a notch in the web at a point where the shear force is high, as the shear is carried in the web (high shear generally occurs in a uniformly loaded beam close to the columns). To ameliorate both of these hazardous conditions, some of the beams had to be haunched (made deeper) in certain locations to safely accommodate the penetrations.[34]

This overlap of the programmatic constraints with the structural and mechanical systems meant every system was intertwined. Whenever one thing moved in the design phase it had an impact on other elements. The hierarchy set up by the structural system accommodated the constant flux in the design phase and helped the architects and engineers to keep track of all the components. This same level of complexity had to be resolved anew for the floor structure over the cellar. This floor was also limited in height, because the further down one excavates, the higher the costs. Thus, the ceiling of the cellar was quite compact with machinery and ductwork. The mechanical needs of the museum along with the extreme temperatures of the glass hot shops, meant that there was significant duct work and piping that went through the floor system, and in order to maintain the desired floor-to-ceiling clearance in the cellar everything had to fit right underneath the floor slab. This floor system was comprised of one-way slabs with band beams; these one-way slabs were to allow slots to go through the floor. As Oki explains: “so many different kinds of layering had to take place, the whole structure from the foundation to the top of the roof was like a Swiss watch.”[35]

The incredibly thin columns that are so crucial to the architectural intent of the interiors presented an engineering challenge. The supports are connected to the roof in such a way that they carry only vertical load.[36] Any lateral load coming from wind, for example, would cause

6.9 Detail. Note the high degree of precision in the detailing where the glass walls meet the roof. SANAA & Sasaki and Partners, Glass Pavilion at the Toledo Museum of Art, Toledo, Ohio, 2007.

© Toshihiro Oki.

the column to carry bending, and bending requires a stiffer section. Since resistance to bending is a function of the shape of the column's cross section, this would have required a much wider column (which is why most columns are "I" shaped or hollow circles and squares). However, even columns loaded only in the vertical direction along their own axis will fail in bending, specifically in buckling. The very careful analysis and design of these slim columns to minimize buckling risk was an interesting research problem according to Guy Nordenson:

> For me, one of the things that has emerged from working on the Toledo project is the interest in the consequence of making things really thin and dealing with the possibility that they might buckle . . . We've had a lot of projects where we are working with things that are on the edge of buckling, either columns or beams that are very thin and so as a result of that we've been doing our own research . . . [This problem] has emerged and it is something that seems to recur and has become more and more interesting the more we learn.[37]

If every column or wall were connected to the roof in the way described above, the whole structure would rack sideways and collapse under wind load. To take these loads, the vertical structure is locked into the horizontal structure of the roof in each quadrant. In one quadrant, this is achieved by the stiff cross section formed by the ¾ inch thick rolled steel wall that forms the enclosure of one of the opaque volumes.[38] It was too costly to replicate this solution in the other portions of the roof, so diagonal bracing is used between specific columns that do connect to the roof in such a way as to pick up lateral load. This cross-bracing is hidden in the sheet rock walls that make up the other opaque volumes.[39] Oki argues that this strategy, whereby the vertical and horizontal loads are separated, making columns do only what they are supposed to do (support dead load) and making other elements do what they are supposed to do, eliminates redundancy and makes the structure more honest and easy to read.[40] Sasaki notes that his deep experience with earthquake engineering in Japan influenced his thinking in this design.[41]

It is clear when investigating the technical design of the building, that the experiential quality of the spaces and the ephemeral aesthetic are made possible only by very careful engineering. Nordenson argues that this kind of study of buildings is important to understand the results of the collaborative process:

> The influence of the collaboration is subtle . . . but it is there . . . It takes some work to draw it out . . . It started out pretty much as Sasaki's design of the structure and it went through a series of incremental modifications as we started to have our impact on the way it was done . . . You really have to look closely at things beyond what people say about them and try to actually study the thing itself to disentangle how it is maybe a different kind of work because of the collaborators who have a hand in it.[42]

The Toledo Museum's Director during the time of construction, Don Bacigalupi, appreciates the impact of the architectural "strategy of dematerialization"[43] facilitated by the careful collaboration; the structural and mechanical systems were minimized and streamlined to achieve lightness and integration with the environment for which so much of SANAA's work strives: "We wanted a showcase for our glass collection . . . SANAA's design changes the way you view the artworks, since you're not seeing them against flat walls . . . they seem to sing in these spaces."[44]

Architect and architectural critic Michael Webb sums up the project:

> The harmony of the proportion is matched by the refinement of the finish and detail. Light is diffused and reflected in flat curved planes that compliment the blown, cut, or modeled vessels on display . . . For Toledo it is a poetic memorial to its industrial past.[45]

Notes

1 Kazuyo Sejima, Yukio Futagawa, and Ryue Nishizawa, "Creating Principles – Structure, Plan, Relationship, Landscape," in *Kazuyo Sejima Ryue Nishizawa, 1987–2006*, Tokyo: A.D.A. Edita, 2005, p. 9.

2 "SANAA: kazuyo sejima + ryue nishizawa interview," Designboom, http://www.designboom.com/interviews/sanaa-kazuyo-sejima-ryue-nishizawa-designboom-interview (accessed March 18, 2014).

3 Ibid.

4 The Hyatt Foundation, "Jury Citation: Kazuyo Sejima and Ryue Nishizawa | The Pritzker Architecture Prize," The Pritzker Architecture Prize, http://www.pritzkerprize.com/2010/jury (accessed August 6, 2013).

5 Mutsuro Sasaki, Toyo Ito, and Arata Isozaki, *Morphogenesis of Flux Structure*, London: AA Publications, 2007.

6 Russell Fortmeyer, "Mutsuro Sasaki," *Architectural Record*, 196(3) (2008): 156.

7 Nina Rappaport, "Sasaki and Partners," in *Support and Resist: Structural Engineers and Design Innovation*, New York: Monacelli Press, 2007, p. 167.

8 Toyo Ito, "Toyo Ito, Liquid Space," *El Croquis*, 147 (2009): 70–88.

9 Although others might argue that while the method produces a rational form within a set of formal constraints already established, it is not analogous to the work of Gaudí who was looking to find a formal solution using the resistance of gravity as the only constraint.

10 Mutsuro Sasaki, Interview by authors, email interview, Tokyo, Japan, September 5, 2013.

11 Mutsuro Sasaki, Interview by Marc Guberman and Nina Rappaport, Tokyo, Japan, August, 2006.

12 Sasaki *et al.*, *Morphogenesis of Flux Structure*, p. 11.

13 Sasaki, Interview by authors.

14 Michael Webb, "Clarity and Light," *Architectural Review*, 220(1317) (2006): 66–70.

15 Ibid.

16 Julie Sinclair Eakin, "Clearing the Way," *Architecture*, 95(10) (2006): 46–51.

17 Clifford A. Pearson, "SANAA's Sejima and Nishizawa create layers of reflections and perspectives in their Glass Pavilion at the Toledo Museum of Art," *Architectural Record*, 195(1) (2007): 78–83.

18 Ibid.

19 Eakin, "Clearing the Way."

20 Webb, "Clarity and Light."

21 Nicolai Ouroussoff, "An elegant, and empathetic, showcase in glass," *New York Times*, September 1, 2006, sect. Arts and Leisure.

22 Ibid.

23 Pearson, "SANAA's Sejima and Nishizawa create layers of reflections and perspectives."

24 Ibid.

25 Sejima *et al.*, "Creating Principles", p. 10.

26 Ibid., p. 151.

27 Ibid., p. 151.

28 Eakin, "Clearing the Way."

29 Toshihiro Oki, Interview by authors, phone interview, New York, NY, July 30, 2013.

30 Eakin, "Clearing the Way."

31 Oki, Interview by authors.

32 Ibid.

33 Ibid.

34 Ibid.

35 Ibid.

36 Ibid.

37 Guy Nordenson, Interview by authors, phone interview, New York, NY, June 14, 2013.

38 Oki, Interview by authors.

39 Pearson, "SANAA's Sejima and Nishizawa create layers of reflections and perspectives."

40 Oki, Interview by authors.

41 Sasaki, Interview by authors.

42 Nordenson, Interview by authors.

43 Pearson, "SANAA's Sejima and Nishizawa create layers of reflections and perspectives."

44 Ibid.

45 Webb, "Clarity and Light."

– 7 –

Queen Alia International Airport

Client	Airport International Group, The Hashemite Kingdom of Jordan Ministry of Trans, Joannou & Paraskevaides (Overseas) Ltd, J&P-AVAX S.A., Airport International Group P.S.C.
Architects	Foster + Partners
Collaborating Architect	Maisam – Dar Al-Omran JV
Structural Engineer	Buro Happold (Conceptual Engineer and Advisors)
Construction	
Quantity Surveyor	Davis Langdon
M+E Engineer	Buro Happold (Conceptual Engineer)
Landscape Architect	Dar Al-Handasah
Lighting Engineer	World of Lights
Additional Consultants	NACO, ADPi, Zuhair Fayez Partnership, Rahe Kraft
Design + Build Main Contractor	Joannou & Paraskevaides (Overseas) Ltd, J&P-AVAX S.A.

Although multiple experts worked together on the design of the Queen Alia International Airport, the case study focuses on the collaboration of Foster + Partners and Buro Happold. We begin with the background on the firms.

Foster + Partners

Foster + Partners, formerly Foster Associates, was founded by Norman Foster in 1967 and is one of the most innovative architecture and design practices in the world. Over the past four decades the practice has pioneered integrated, sustainable design solutions through a strikingly wide range of work, from urban master plans, public infrastructure, airports, civic and cultural buildings, offices and workplaces to private houses and product design. Based in London, with studios worldwide, the practice has an international reach, with buildings on six continents. Since its inception in 1967 it has received more than 640 awards for excellence and won over 100 national and international competitions.

Projects have included the redevelopment of the Reichstag, the New German Parliament in Berlin and the Hongkong and Shanghai Bank Headquarters, as well as the revolutionary Masdar City master plan, a mixed-use, high-density development outside Abu Dhabi, which is the first low-carbon, zero-waste desert city. The work demonstrates decades of accumulated expertise, sparking critic Paul Goldberger to say, "Foster buildings . . . don't show their effort."[1] In describing the trajectory of the firm's work, Foster said, "The only constant is change and change is about evolution, it's about innovation, it's about new ways of doing things."[2] Foster designed the office's collegiate structure, which focuses on collaboration, innovation and research, enabling a rigorous approach to the work, and ultimately, longevity for the office.

With around 1,000 people working in the offices in London and numerous satellite offices around the world, Norman Foster restructured the firm's organization in 2004. The office was divided into six design groups, each lead by a Senior Partner, working on a diversity of projects, throughout the world. These design groups are supported by specialist teams including materials and environmental research, product design, space planning, interior design, communications, graphic design, visualization, model-making and 3D computer modeling. "To use an urban analogy, if the six groups can be thought of as individual buildings, then the network of specialist support teams is the infrastructure that binds them together."[3] In 2010, Foster positioned integrated design at the forefront of the firm's mission and added two engineering groups. The engineering teams are actively growing, with over 60 engineers working in house at the time of writing.

Buro Happold

Buro Happold was founded by British engineer Sir Edmund 'Ted' Happold in 1976. Happold worked at Arup before starting an office in Bath to partner with Frei Otto on the King's Office and Council of Ministers project in Saudi Arabia. The early work in form-finding and complex geometries seeded the firm's commitment to research and design innovation, which has continued throughout the office's nearly 40-year history. In Peter Davey's *Engineering for a Finite Planet*, Ted Happold is quoted as saying that engineering, "is intensely creative; at its best it is art in that it extends people's vision of what is possible and gives them new insights."[4] Buro Happold has a formidable record for design innovation, which is why they are enlisted to work on some of the most complex projects in the world. The firm now employs 1,400 employees offering a wide range of services in 27 offices across the globe.

Buro Happold's London hub employs nearly 300 engineers. Wolf Mangelsdorf, Head of Structural Engineering in the London office, wrote of the firm's philosophy in his article *Structuring Strategies for Complex Geometries*:

> [W]hen designing complex three dimensional shapes and geometries, structural engineering has to be a creative contribution to the design process, so that a full integration and coordination of aesthetical and physical aspects can be achieved. This relies completely on the development of engineering concepts that understand and facilitate the design, and at the same time close collaboration with the architect, manufacturer and other design disciplines.[5]

The London office has worked on such world-renowned projects as the British Museum Great Court with Foster + Partners, which won an Institute of Civil Engineers "Special Award" and the London 2012 Olympic master plan and numerous other engineering services for the complex that were completed for the 2012 Olympic Games.

Introduction to Queen Alia International Airport: Design Influences

When examining the body of Foster + Partners' portfolio, the work is incredibly diverse; however, there are a few recurrent themes. Exposed structure is often used as a means of providing clarity and elegance to the form and experience of the built work. In the 1970s and 1980s, the firm was viewed as championing the "high tech" style. In a 1994 article, "Architecture and Structure," Foster described that "The visual dimension of a structure is also its spiritual dimension: how it will look, and how it will work, become conceptually inseparable throughout the process of design."[6] Although the tone and aesthetic of the work has evolved with the firm, exposed structure continues to be a feature of many projects—however, every design is a unique response to the site, demands of the brief, culture and many different users.

Foster describes the importance of the experiential qualities of the architecture and the goal to "reinvent concepts like an airport in such a way that the experience of an airport will be uplifting. An airport has gotten to the point of crowds and security that it's a kind of reviled building type."[7] Foster + Partners revolutionized the design of airports, first with Stansted Airport in London (1981–1991) where the designers shifted the services under the floor in order to create a lighter roof structure with skylights. Given the plans to phase growth of Stansted, the architects decided to use a modular system, which proved highly influential for later projects, including the Queen Alia International Airport.

Foster describes the firm's approach for their first airport,

> At Stansted the base or "trunk" of the trees are literally rooted in the distribution of air and artificial lighting from the undercroft below. The "branches" spread out

7.1 The airport is envisioned as a gateway to Jordan. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Courtesy of Nigel Young/Foster + Partners.

> to support the most elegantly minimal roof, whose function is only to provide shelter from the elements and to let in light from the sky above. Compare this with the massive roof and supporting structure for a traditional airport with its need to carry the weight of the mechanical equipment above the roof and below it all the usual ductwork, fluorescent lighting, cables and suspended ceilings. By comparison, our concept for Stansted is radical even if it does mark a return to an earlier tradition of less mechanistic buildings—to suggest a newer generation which are elegantly comfortable but also energy conscious.[8]

In addition to a reduction in energy consumption and providing flexibility, the design also dramatically transformed the airport experience, and subsequently, the firm has been commissioned to design multiple airports and transport stations. These include Chek Lap Kok Airport in Hong Kong, completed in 1998; Beijing Airport, which, until recently, was the largest building in the world and constructed in just four years by 50,000 workers in time for the 2008 Beijing Olympics; and the first station for commercial space transport, Spaceport America, to be completed in 2014.

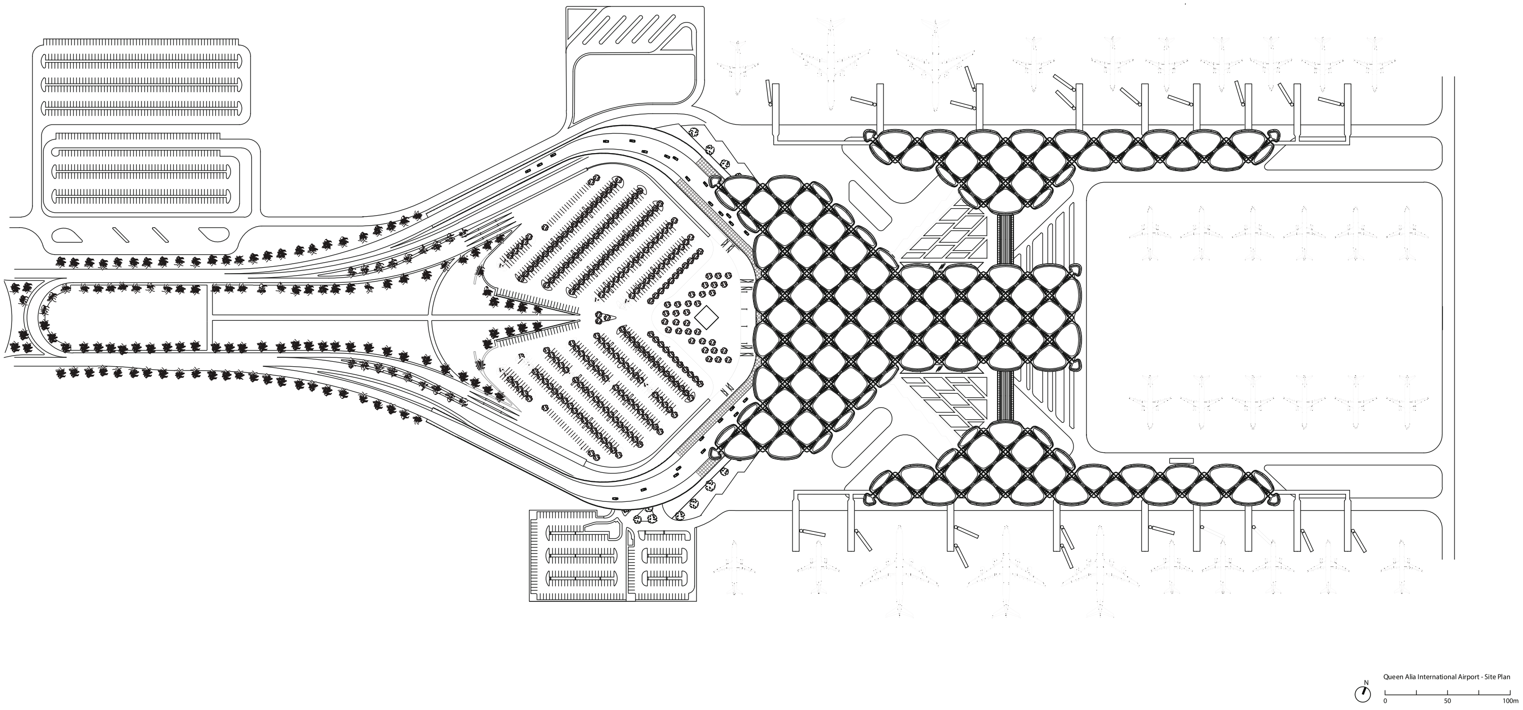
In 2005, Foster + Partners was approached by the Jordanian Royal Development Company to produce designs for a number of projects, including the airport located 35 kilometers from the capital city of Jordan, Amman. The customer base was growing, and the

7.2 Aerial view of the Queen Alia International Airport showing the modular structure. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Courtesy of Nigel Young/Foster + Partners.

clients envisioned that a new airport would create a gateway and increased tourism for the country. The team composed of architects and engineers did an initial ten-week study to show how the existing airport could be expanded. This preliminary scheme was presented to the royal household and was well received. Very shortly into the development, however, the team determined (with full support of the client) that in looking towards the future of the airport, a ground-up strategy would have more longevity than remodeling the existing structure. The World Bank funded further design work, which was developed into a tender package. The project construction was an $800 million, privately funded venture and is operated by Airport International Group (AIG), a consortium of Jordanian and international companies.

The 100,000 square meter building is symmetrically organized with two terminal piers extending from either side of a central building that contains duty-free shops, newsstands, banks, restaurants and passenger lounges, as well as offices and storage. The two piers hug a central courtyard filled with trees that provide shade for families greeting visitors and also filter air before it moves through the building. The glazing surrounding the perimeter provides an open feeling and a visual connection to the airport runways as well as natural daylight. Heat is mitigated with a louver system and the use of thermal mass, which is essential for an environmentally responsible building in the extreme temperatures of Jordan. The concrete enables passive environmental control as the building slowly warms up throughout the day and releases heat in the cool evening hours.



7.3 The 100,000-square-meter project is organized symmetrically around a central axis. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Courtesy of Foster + Partners.

7.4 The mullions curve to reflect the domed roof. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Courtesy of Nigel Young/ Foster + Partners.

The Team and Working Methods

The team that designed the building included architects and engineers as well as many of Foster + Partners' in-house specialists. The Partner in charge of the project was Jonathan Parr, a Deputy Group Leader at Foster + Partners, and the project architect was Associate Partner, Darryn Holder. Parr started working with Foster + Partners in 1992 on Hong Kong International Airport, HACTL cargo terminal and the GTC transportation building. The London office of Buro Happold was also part of the initial design team and included Senior Partner and Chairman, Mike Cook, Senior Partner and environmental engineer, Neil Billett and Group Director and structural engineer, George Keliris.

Keliris describes the working relationship:

> We've done a lot of work with Foster's office and Jonathan Parr around the world including projects in Jordan. Being in London was quite useful, because much of the discussion was face-to-face, and this allowed Buro Happold to talk through the designs and influence them from the engineering perspective.[9]

The multidisciplinary team would gather around a table, discuss ideas and then Foster's office would work through the design ideas through visualization. During this process, Keliris notes, "We were challenged by the architects to not use a typical, normative structure, but something that was iconic and different. That meant that we challenged the architecture as well, ensuring that the solution was the result of our in-depth collaboration."[10] Keliris goes on to describe the rewarding aspects of working as a "creative engineer" and credited offices like Foster's that encourage innovation in structural design.

Foster + Partners has always partnered closely with engineers, and Norman Foster made a decision to integrate engineers into the office in 2010. The QAIA project was designed before this restructuring, but the working mode used on the project was very similar to what is described in the firm's mission of integrated design:

> Foster + Partners understands that the best design comes from a completely integrated approach from conception to completion. We have a strong creative team, in which structural and environmental engineers work alongside the architects from the beginning of the design process. By doing so, we believe that they can learn from one another and combine their knowledge to devise wholly integrated design solutions.[11]

The A/E design team evolved to include members of support groups including the Specialist Modeling Group (SMG). Xavier De Kestelier, a Partner at Foster + Partners and joint head of SMG, has worked with the firm since 2002, supporting project teams in areas of computation and geometry at various stages from conceptual development to rationalization and construction. De Kestelier explains:

> We always try to get engineers involved really early. The form might be driven by various things at the same time—aesthetics, rationalization, structural optimization—all these things probably have their own perfect shape and it's a conversation amongst everyone to get that right. It's not like we make the shape we want and then give it to the engineer to figure out how to make it stand up—it's always a conversation.[12]

For Queen Alia International Airport, the specialist group worked with the multidisciplinary team to develop modeling strategies, constructability rationalization and fabrication support.

Development of the Structure and Fabrication

PARR relates that "the decision to make the roof out of largely precast components sitting on an otherwise very straight-forward in-situ concrete slab was decided quite early on."[13] A precast, modular roof structure was chosen for a number of reasons. Firstly, the modular system had proven effective in Stansted Airport, which provided QAIA's "genetic code."[14]

7.5a and b Precast components craned to the site. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Courtesy of Nigel Young/Foster + Partners.

Because there was a Design and Build contract, the contractor came into the design process early on and played a pivotal role in moving forward with the decision to employ the modular system to facilitate construction. The systematic approach was also critical to creating the kind of flexibility that had proven so successful in Stansted Airport. As Parr points out, "Airports, like many infrastructure projects, respond to a need at a given time, but they have to be flexible."[15] Stansted grew in scale during construction and the Queen Alia traffic is also growing at a faster rate than expected. Since the number of passengers is anticipated to increase from 3.5 million to 12 million by 2030, the architects and contractors are already moving forward with an addition, a prospect that is made considerably easier through the modular design.

The shape of the modules grew from a desire to create a more fluid and welcoming environment, and the efficient geometry of the umbrella structures enables wider spans. The 24 meter column spacing opened up the floor areas for circulation, permitting visitors to see signage from a distance and more easily navigate the airport. The domed, warm-hued concrete creates a grand, monumental space, thereby producing an uplifting and celebratory experience. There are 127 modules composed of a simple set of four module types: a field unit, a half unit, edge and corner units. Each module has the same cantilever and shared dimensions, which permitted an efficient use of formwork and assured constructability. According to Parr, "The beauty of the modular system is that once you work out the initial kinks in manufacturing, the rest of the building follows suit. It's a highly repetitive building, which means that it's not

7.6 Interior view showing the openness afforded by the umbrella structures. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Courtesy of Nigel Young/Foster + Partners.

constantly setting new challenges; once you figure out how it works, it continues to work the same way."[16]

This approach to structure is consistent with Foster + Partners' search for integrity in their design work and desire to convey buildable ideas to their clients. Parr remarks that,

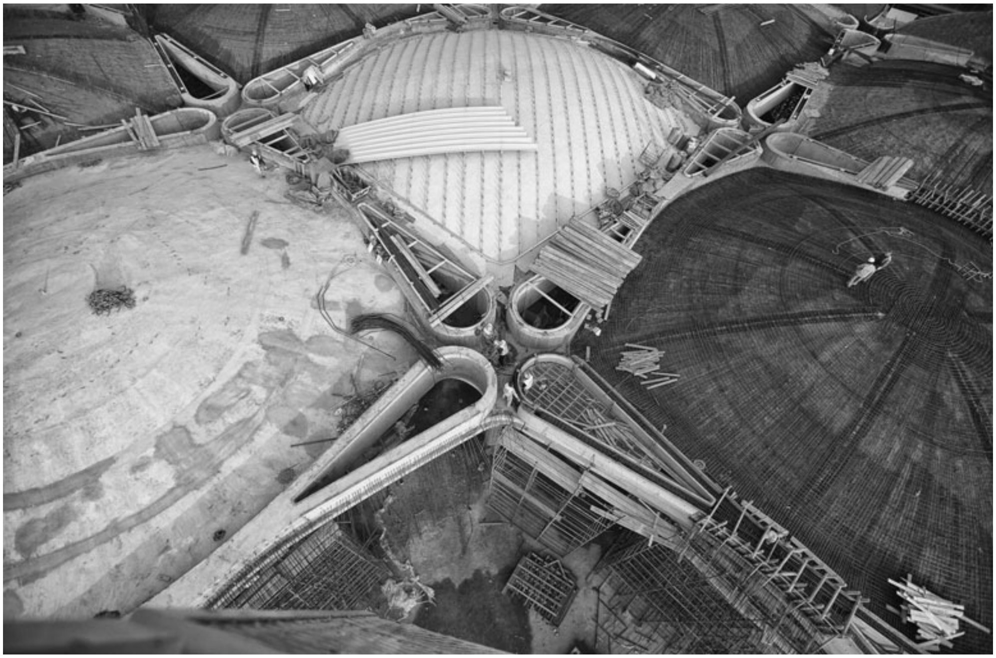
> From the early ideas, we were always mindful of how this would be built. We also wanted to maintain a degree of flexibility and indicated that it would be made out of components so that the client would have the comfort of knowing that what they see in visualization is eminently practical and buildable and it's not just an image . . . We always want to be direct with our clients to show them what something really will be so that they are comfortable at every step of the project. It's a very honest way of working and part of a process, and we hope that it gives people reassurance. So even in the early days, we were showing a roof made of components.

The form of Queen Alia International Airport has been compared to desert palms and Bedouin tents that give the structure a feeling of place. The openings in the shells provide natural light (and also remove weight from the structure), reducing energy loads for lighting the large terminal. Keliris describes that,

> The shells have an enormous thrust within them. Foster's office wanted this enormous, heavy, hard-working roof structure to be light and elegant, so we

7.7 Openings in the shells provide natural light and reduce the energy load for the building. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Courtesy of Nigel Young/Foster + Partners.



7.8 The precast X-beams and roof shells. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Courtesy of Nigel Young/Foster + Partners.

> introduced openings. We were striving for structural efficiency. In the end, our ideas converged and we ended up with a structural solution that wasn't too complex in that we formed precast X-beams that follow forces and allow for the openings making architecture and structure integrated.[17]

The modular system also made sense for prefabrication. The contractors set up a batching plant adjacent to the site. In describing the concrete, Parr said that it was composed of "locally sourced materials, which apart from the very fact that that's the sensible and sustainable thing to do, it means from an emotive and symbolic point of view, the building is made of Jordan."[18] With a reliable supply of material, this assured that the quality and texture of the concrete would remain consistent throughout the project.

The formwork for prefabrication was manufactured at a ship-building plant in Greece that had experience in molding steel in doubly curved shapes. The steel enabled a very smooth, crisp finish and stature to the concrete and also allowed the contractors to reuse the molds in a way that timber would not have permitted. The manufacturers were provided with a digital model by Foster + Partners' Specialist Modeling Group that enabled the ship builders to program their Computer Numerically Controlled (CNC) machines to cut the 5mm-thick steel and mold it to create the formwork for the roof shells. They also fabricated the steel formwork for the X-beams, which were 19.4 meters long, but needed to be cut in half for transport to the contractor's fabrication plant in Jordan.

7.9 The modular roof allows for a systematic approach to construction. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Courtesy of Nigel Young/Foster + Partners.

7.10 Foster + Partners Smart Geometry Group developed a very detailed precise model that was used for fabrication and construction administration. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Drawing courtesy of Foster + Partners; photograph courtesy of Nigel Young/Foster + Partners.

There are 308 X-beams that weigh just over 19 tons each and form a network that supports the roof shells. Each of the 127 domes is comprised of parts, resulting in 720 shell components that needed to be transported to the site with a crane. The parts were made at the off-site facility in assembly-line fashion, identified with a code number and lifted with the crane a short distance to become part of the building. In order to insure that these parts were as lightweight as possible

7.11 Interior view of one of the terminals. Foster + Partners, Buro Happold, Queen Alia International Airport, Amman, Jordan, 2013.

Courtesy of Nigel Young/Foster + Partners.

(relatively speaking), they used "a high-performance steel fiber-reinforced mix with a maximum aggregate size of 3/8 in."[19]

A cast-in-place strategy was used for the concrete to the tops of the columns including the foundation, pile caps and ground floor slab. One area of columns is double height to allow for a mezzanine level. The roof, on the other hand, including the column heads, beams spanning between and roof shells (composed of eight pieces each) were all precast. Once positioned on site, a layer of in-situ concrete was poured on top of the roof to stabilize the structure and allow for tolerance in assembling each dome's eight parts. It was a challenge to level all the columns so that the roof would sit squarely on top, but given the repetition of the system, the leveling strategy could be applied to each column.

Despite its remarkable presence and character for the project, raw concrete is not very common in Jordan and the designers needed to do some convincing to preserve the bare material. Parr describes that:

> Concrete can do fantastic things, and in our eyes, can produce a beautiful product; it's not merely structural—it can provide character. We were so pleased with the quality of the finish that was being achieved in the early mock-ups that we became convinced that the concrete should be exposed. The light had a lovely reflection on the concrete, so we believed that it should be left in its natural state, without finishes. It's been appreciated by the world press, the people who go there, and contractors

> . . . At the opening ceremony, people said that it was the right thing to do, it makes it special. That's all we were trying to do, we were just trying to make the building special for everyone who will use it and for the people who took part in making it and for the people who run it and the people of Jordan. It really is something that belongs to them in a very special way and on that level is why it succeeds as a building more than anything else, it really does belong there; it comes from the country.[20]

Notes

1 *How Much Does Your Building Weigh, Mr. Foster?*. Film, New York, Art Commissioners, 2012.

2 ArchDaily, "AD Interviews: Norman Foster," ArchDaily, http://www.archdaily.com/280814/ad-interviews-norman-foster/ (accessed October 12, 2012).

3 Mouzhan Majidi, *Catalogue: Foster and Partners*, Munich: Prestel, 2008, p. 327.

4 Peter Davey, *Engineering for a Finite Planet; Sustainable Solutions by Buro Happold*, Basel: Birkhaüser, 2009, p. 9.

5 Wolf Mangelsdorf, "Structuring Strategies for Complex Geometries," *Architectural Design*, 80(4) (2010): 40–45.

6 Norman Foster, "Architecture and Structure," www.fosterandpartners.com/data/practice-data/essays/essay14 (accessed August 2013).

7 ArchDaily, "AD Interviews: Norman Foster."

8 Foster, "Architecture and Structure."

9 George Keliris, Interview by authors, phone interview, London, UK, June 21, 2013.

10 Ibid.

11 http://www.fosterandpartners.com/profile/integrated-design/ (accessed March 18, 2014).

12 Xavier De Kestelier, Interview by authors, phone interview, London, UK, June 18, 2013.

13 Jonathan Parr, Interview by authors, phone interview, London, UK, June 18, 2013.

14 De Kestelier, Interview.

15 Parr, Interview.

16 Ibid.

17 Keliris, Interview.

18 Parr, Interview.

19 T. R. Witcher, "Jordan Airport Extension Reflects Local Influences," American Society of Civil Engineers, http://www.asce.org/CEMagazine/Article.aspx?id=23622325664 (accessed March 18, 2014).

20 Parr, Interview.

– 8 –

Simmons Hall at MIT

Client	Massachusetts Institute of Technology
Architects	Steven Holl Architects: Steven Holl and Tim Bade
Local Architects	Perry Dean Rogers and Partners
Structural Engineering Design	Guy Nordenson and Associates
Project Engineers	Guy Nordenson and Associates and Simpson, Gumpertz & Heger
Mechanical Engineer	Ove Arup & Partners
Lighting Consultants	Fisher Marantz Stone
General Contractor	Daniel O'Connell's Sons

The design of Simmons Hall involved many firms and individuals, but the following discussion focuses on the partnership between Steven Holl Architects and Guy Nordenson and Associates.

Steven Holl Architects

Steven Holl Architects (SHA) is a New York-based firm founded by Steven Holl. Steven Holl studied architecture at the University of Washington, but considered dropping out to become a painter. A scholarship to travel to Europe provided inspiration to stay in the field: "I won a position to study abroad and was suddenly air-lifted from the sleepy, shingled regionalism of Seattle to Rome . . . in the tremendous space of the Pantheon, I first felt the passion, the forceful capacity, of architecture to engage the senses."[1] Holl later went on to graduate study at the Architectural Association School of Architecture in London in the late 1970s at the invitation of Alvin Boyarski. There he encountered numerous emerging leaders in the field as colleagues and teachers, including Zaha Hadid, Rem Koolhaas, Leon Krier, and Bernard Tschumi.[2]

Holl started his practice, SHA, in 1976 and the firm has gone on to amass a considerable body of work and has won numerous awards. SHA won its first design competition in 1988, the International Library Design Competition to expand and renovate the Amerika Gedenkbibliothek, the American Memorial Library in Berlin. This was one of Holl's first collaborations with engineer Guy Nordenson.[3] During the 1990s he designed the Chapel of St. Ignatius in Seattle, an AIA National Design Award winner, and Kiasma, the Museum of Contemporary Art in Helsinki. In 1998, he was awarded the prestigious Alvar Aalto Medal for creative contributions to the field of architecture. In addition, Holl won the New York American Institute of Architects Medal of Honor, the French Grande Médaille d'Or, and the Smithsonian Institution's Cooper-Hewitt National Design Award in Architecture. In the 2000s his designs for the School of Art and Art History at the University of Iowa, the Pratt Institute in Brooklyn, and the Herning Museum in Denmark received much acclaim. He was named America's Best Architect by *Time* in 2001, in 2010 he was awarded the Royal Institute of British Architects (RIBA) International Award, and in 2012 he was the AIA Gold Medal winner.

Christopher Platt, Head of the Mackintosh School of Architecture where Holl was recently commissioned to design a new building on the campus of Charles Rennie Mackintosh's famous Glasgow School of Art, describes the preoccupations of Holl's work as "Exploration of place, sensory experience and function . . . Holl orchestrates transparency, translucency, texture, opacity, color, material and scale in order to heighten our awareness of who and what we are."[4] Holl writes extensively about his architectural work and teaches Architecture at Columbia University and has done so throughout his career. His own writing reveals a deep study of the haptic and the experiential as central to his design research:

> Architecture intertwines the perception of time, space, light and materials . . . the phenomena which occur within a space of a room, like the sunlight entering through a window, or the color and reflection of materials on a surface, all have integral relations in the realm of perception . . . Experience of phenomena—sensations in space and time as distinguished from the perception of objects—provides a "pre-theoretical" ground for architecture . . . Phenomenology in dealing with questions of perception, encourages us to experience architecture by walking through it, listening to it.[5]

Holl spends part of each day making watercolor paintings, some general and some project-specific.[6] The design concepts for his architecture emerge from this process. New techniques are developed to execute these concepts and Holl is clear about the need to embrace this process and to strive for new ideas: "Given the myriad possibilities, I am amazed at the repetitive nature of our environment. We should resist the easy route of homogeneity."[7]

Guy Nordenson and Associates

Guy Nordenson studied civil engineering at MIT and UC Berkeley. While in school, he interned with sculptor Isamu Noguchi and, through him, went on to work with architect Buckminster Fuller. After graduating with a Masters in Structural Engineering, he worked for a prominent engineering firm, Weidlinger Associates, moving shortly thereafter to Ove Arup. He became a director there before opening his own firm, Guy Nordenson and Associates (GNA) in 1997. Since 1995 he has also taught structural engineering to architecture students at Princeton University.

Nordenson believes that engineering and architecture are not autonomous arts.[8] Thus, GNA focuses on collaborative practice with architects and designers. The firm has engaged in structural design for the Museum of Modern Art (MOMA) expansion in New York with architect Yoshio Taniguchi, and the Jubilee Church in Rome finished in 2003 with architect Richard Meier. Other notable contemporary projects include the Kimbell Art Museum Expansion in Fort Worth, Texas, designed by Renzo Piano, the New Museum of Contemporary Art in New York City with SANAA and Sasaki (see Chapter 6), and the National Museum of African American History and Culture designed by Freelon Adjaye Bond/SmithGroup.

Nordenson occupies a prominent role among New York City structural engineers and designers. In the aftermath of 9/11, he led a volunteer effort to triage four hundred buildings impacted by the World Trade Center's collapse. In 2003, he was the first recipient of the American Academy of Arts and Letters Academy Award in Architecture for contributions to architecture by a non-architect. He has served as Commissioner and Secretary of the New York City Public Design Commission since 2006. His project "On the Water," researching the risks and potential amelioration strategies in the face of rising sea levels, led to the workshop and exhibit "Rising Currents" in 2010 at the MOMA. In 2010 GNA was awarded an NCSEA Excellence in Structural Engineering Outstanding Project Finalist for the Yale Hillhouse Pedestrian Bridges.

The Collaboration

Steven Holl is an architect with a concern for structural expression in his design work. He rejects the industry reliance on standard structures with a non-structural skin as the differentiating element: "If that is going to be the future of architecture, then I want to do something else."[9] Speaking about the challenges to the integration of architecture and engineering in contemporary design practice, he asserts:

> The tendency today to opt for a complex skin and give in to developers building inexpensive and rapidly constructed interiors has become a challenge . . . I feel that a concept should integrate structure into the meaning, the basic experience of a work in space and light.[10]

He extols the design imperative (that he argues is shared by some of the most significant architects of the twentieth century) to attempt to reconcile load carrying and enclosure systems:

> In most buildings, structure is about 25 percent of the cost and 30 percent of the material. So if you don't bring structure to bear on whatever it is you are doing as an architect, then I think somewhere it's not working. It is not reconciled. Le Corbusier always incorporated the structure, as did Kahn, and Mies. I am interested in maintaining an integral relation of the idea through the structure, the space, and the experience.[11]

When Holl won the competition in 1988 to expand and renovate the Amerika Gedenkbibliothek, it was to be the beginning of a long-standing collaboration with Guy Nordenson: "We work together on design from the very first concept stage. With watercolor concept diagrams pinned to the wall, we have discussions and debates about alternative design concepts."[12] Speaking specifically about working with Nordenson on Simmons Hall, Holl is quick to acknowledge Nordenson's role in the overall design: "It was a process of true collaboration where the give and take continues through the entire process."[13]

Nordenson argues that the nature of an engineer–architect collaboration depends on the predisposition of the parties involved and is often best achieved in the context of a long-standing working relationship:

> My experience is that collaboration is very site specific, it depends a great deal on who you are working with. Most of the architects I have worked with, I have known for a long time, and started working with them when we were both relatively early in our careers, Steven Holl for example, is someone I have worked with for over 30 years.[14]

Speaking about the challenges to collaborative practice between architects and engineers, Nordenson notes:

> the fundamental challenge comes up every time you talk to anyone who is not in the field about what it is that engineers and architects do . . . It inevitably leads to "well what's the difference between you and an architect?" . . . then that leads to a realization: "Oh I understand now, you make it stand up" which I think is often quite accurate.[15]

However, this linear process of "instrumental application of the engineering disciplines,"[16] where the engineer is required only to get the job done without altering the architect's parti, is not the process that interests Nordenson: "For someone like me that is not all that interesting because there really is no opportunity for interchange."[17] However, he also notes that in some cases, particularly new collaborations, engineers have to "earn their place" at the design table by proving to their architecture partners that they have the skills and vision to contribute to the process. In a current project, the Kimbell Museum with Renzo Piano, which is a first-time collaboration, his firm's input into the complex roof design has evolved from a back and forth process. The engineers at GNA produced physical and digital 3D models and deliberately worked in the same medium as the architects to make the case for their proposed scheme, "eventually getting to a point where we were working in parallel because they respected what they were seeing and were happy to let it take its course."[18]

Speaking specifically about his working relationship with Holl, he reports that interestingly the nature of the collaboration can vary from project to project:

> The way we work together is very much a function of the way that Steven works, and the collaboration is best timed within his natural process . . . He'll often come to a conversation on a project with some pretty well formed ideas of what the material and the structure is going to be so that triggers the conversation and often times that takes us to where we will end up. For example, we did a project together in Iowa for an Art History and Art School and there is a stair that was built that looks a lot like the initial watercolor. So in that instance the collaboration was all about working together to execute what at the outset was a really beautiful design. But then there is the other end of the spectrum with Steven, which is the design for the dormitory at MIT, where the way we made it was something that took some time to develop, and I think [our collaboration] had some impact, on how one feels about the building.[19]

It is clear that both designers are predisposed to collaboration and have doubtless learned a great deal from each other in a long-standing working relationship.

The Design of Simmons Hall

In 1999, Massachusetts Institute of Technology in Cambridge, Massachusetts hired Steven Holl to design a new residence hall. Simmons Hall is ten stories tall, 330 feet long, and provides dorm accommodation to 350 students. A primary goal of the project was to promote interaction among the students both around and inside the building.[20] To this end, the program incorporates a theatre, a night café and a dining hall at street level. "Our initial design concept was a *folded street.*"[21] That proposal had a street-like ramp that climbed up through the building. "We took this rather radical design through to 50% schematic design, when the University informed us that a 100ft height limit would be enforced on the site. We restarted with a concept of porosity, which characterized our entire master plan of four future dormitories along Vassar Street."[22] The initial concept watercolor for this final design demonstrates this concept of sectional cuts for light and air.

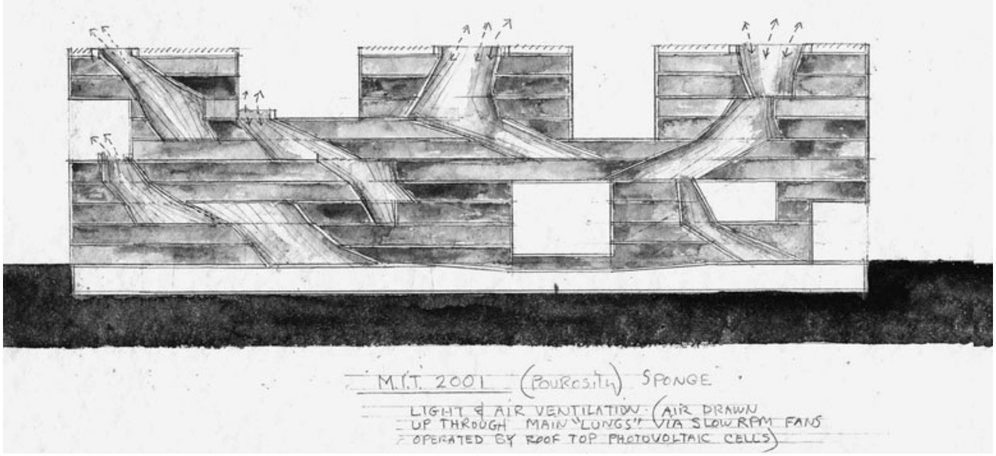
8.1 Note the filled-in window openings that accommodate areas of higher stress, which occur around openings and in areas where the façade acts as a beam or cantilever to span the openings in the façade. Steven Holl Architects and Guy Nordenson and Associates, Simmons Hall at MIT, Cambridge, Massachusetts, 2002.

© Paul Warchol.

Yukio Futagawa describes the concept as "[transforming] a porous building morphology via a series of programmatic and bio-technical functions."[23] Looking at the exterior of the building, one sees five large openings in the façade that faces Vassar Street: these denote the entrance, roof terraces and other outdoor space. Holl argues that a dormitory is a special housing type, neither permanent like an apartment building, nor transient like a hotel, and as such, must be designed with spaces of social condensation to bring people together. This lead to a design strategy of porosity;[24] inspiration was drawn from sea sponges that are "complex, organic, [with a] structure that exhibits an incredible variety of spaces."[25]

Inside the building, extra wide 11ft corridors function like city streets and they are punctured at strategic locations with free-form atria that extend through a number of floors. In and around these atria are the public spaces of the residence hall such as group study rooms and student lounges. These atria also cut from the front to the back of the building and where they intersect with the exterior they cut an organically shaped opening in the wall.

There were ten "houses" within the dorm and so ten clusters were included. The glazed openings draw natural light into the interior and public programs of the building (something usually missing from double-loaded corridors of typical residential halls). The free form spaces created by these atria and openings are described as the "the lungs of the building bringing natural light down and moving air up through the section."[26] These spaces with heavy concrete

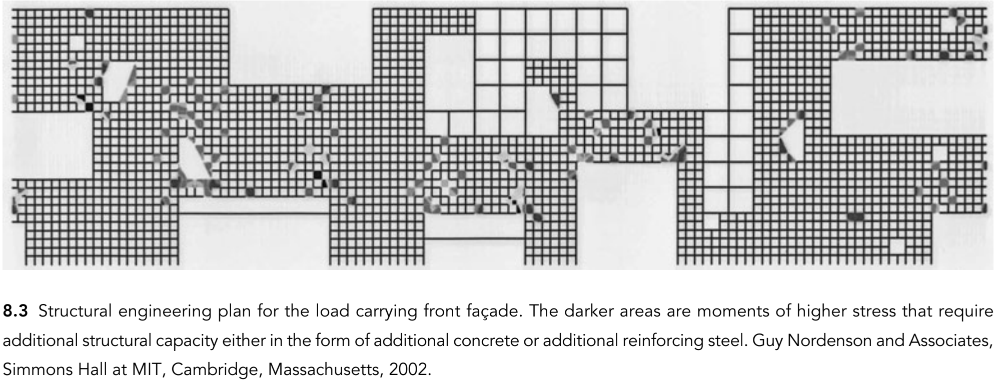


8.2 Steven Holl's watercolor concept sketch showing the initial concept for the final design of the residence hall with organic shaped atria that puncture the floor plates and act as the lungs of the building (note the reference to photovoltaic cells on the roof, these were ultimately excluded from the final project for cost reasons). Steven Holl, Simmons Hall at MIT, Cambridge, Massachusetts, 2002.

© Steven Holl Architects.

walls and large openings are simultaneously cavern-like and filled with light. The free form shapes intrude into some of the corridors and dorm rooms, which are among the most coveted by the students.[27]

The site for the building on Vassar Street is about 1000 feet from the Charles River. As is often the case around tidal estuaries, the soil conditions were not ideal; the soil was too unstable for piles and the bedrock was too far down to reach. The weight of the structure is spread out across a 4ft thick solid concrete mat foundation.[28] The mass of the building is largely carried by the precast concrete façade, which allows for structure and enclosure in one. Holl describes:



8.3 Structural engineering plan for the load carrying front façade. The darker areas are moments of higher stress that require additional structural capacity either in the form of additional concrete or additional reinforcing steel. Guy Nordenson and Associates, Simmons Hall at MIT, Cambridge, Massachusetts, 2002.

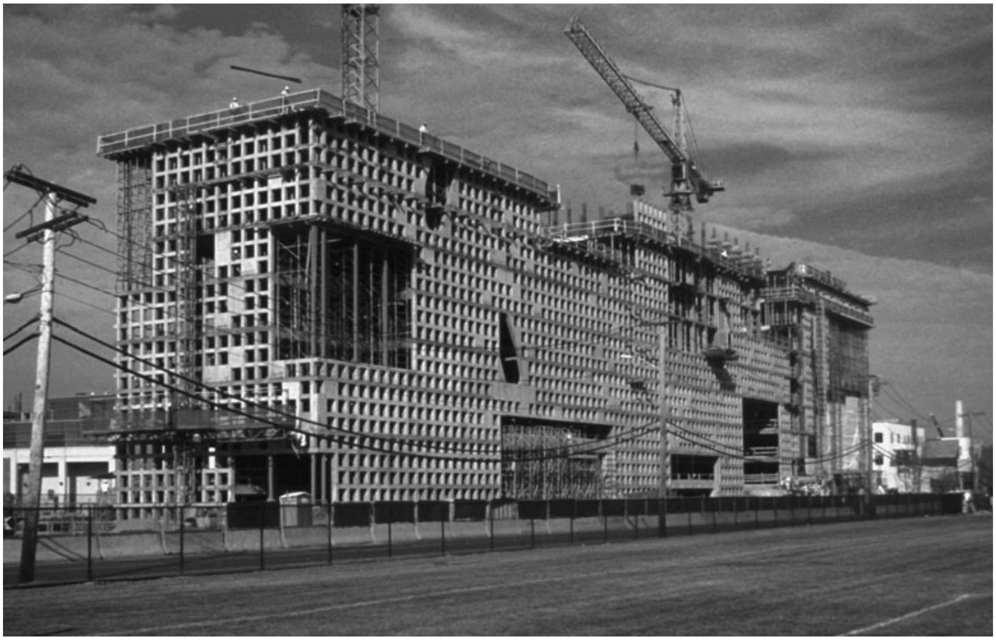
© Guy Nordenson and Associates.

8.4 Precast concrete modules for the façade of Simmons Hall under construction at the Canadian manufacturing facility. Steven Holl Architects and Guy Nordenson and Associates, Simmons Hall at MIT, Cambridge, Massachusetts, 2002.

© Steven Holl Architects.

> Guy suggested the prefabricated concrete sections of perfcon, which fuses window, wall and structure. Guy found the Canadian pre-caster who produced the 291 precast wall panels. They are all slightly different due to the different structural loads.[29]

Around much of the perimeter, the gridded structure acts just like beams and columns do in a normative structure, or like a wall with holes punched for windows. The horizontal pieces span a very short distance and the load flows down the vertical pieces to the foundations below. The horizontals also lend considerable lateral stability against wind loads. It is, however, at the moments where the façade must bridge or cantilever over the larger openings that the true innovative merit of the structural scheme can be seen. In these locations, the grid (all fully moment-connected due to the embedded steel reinforcement) acts like a Vierendeel truss, resolving the large bending forces that would otherwise require a deep heavy beam, into much smaller tension and compression forces in the horizontal members held apart by the vertical member. The smaller openings also lead to higher forces in the adjacent grid. The parts of the grid with larger forces (due to openings large or small) required a combination of filled-in window panels and increased steel reinforcing. Naturally the irregularity of the structure and the differing loads that each piece would carry required careful study with an iterative computational process. The indeterminate structure required non-linear structural analysis



8.5 Simmons Hall under construction. Steven Holl Architects and Guy Nordenson and Associates, Simmons Hall at MIT, Cambridge, Massachusetts, 2002.

© Steven Holl Architects.

8.6 Guy Nordenson visits Simmons Hall interior under construction. The precast modules that make up the skin of the building are structure and façade in one system, with the openings providing ample daylight into the residence hall. Steven Holl Architects and Guy Nordenson and Associates, Simmons Hall at MIT, Cambridge, Massachusetts, 2002.

© Guy Nordenson and Associates.

that was recalculated every time an opening changed or different window panel was filled in.[30] This process intrigued both designers, with Nordenson explaining that "We liked the indeterminacy based on how you activate the information,"[31] while Holl enjoyed the resulting whimsy that could "also meaningfully [make] visible a systematic way of dealing with the variation."[32]

Both Holl and Nordenson pushed for the concrete scheme, while the clients would have preferred steel as they wanted the building finished as quickly as possible.[33] Steel buildings are generally quicker to build and are often cheaper. But there were a number of advantages to a concrete building, particularly one with a load-carrying façade: the large thermal mass, which is inherently insulating, helps to keep the building cool in summer and warm in winter. In fact, while the building has limited supplemental air conditioning, it is largely cooled through passive means. Concrete as a structural material is also highly sound insulating and fire resistant, which makes it a great choice for a dorm building. Each single dorm room has nine operable windows that measure over 2ft × 2ft. The size and layout of the windows were designed to allow views

8.7 Simmons Hall interior staircase under construction. Note the use of rough boards to line the formwork of the cast in place concrete, in deliberate contrast with the highly controlled and refined finish of the precast elements. Steven Holl Architects and Guy Nordenson and Associates, Simmons Hall at MIT, Cambridge, Massachusetts, 2002.

© Guy Nordenson and Associates.

for both standing and sitting occupants.[34] The window jams are 18 inches deep, so they provide shade from the high summer sun while allowing the lower winter sun to penetrate the rooms.[35]

This system proved economical and the digital modeling of the molds in the pre-casting process allowed for incredible precision and refinement in the final product:

> Only one of the six thousand panels was defective—it had a small chip. The site-cast concrete, on the other hand, was very crude. We intentionally played up the difference between the two systems by lining the forms of the site-cast work with random boards.[36]

This contrast is particularly evident in the grand lobby staircase.

To prove to the client that concrete was a viable choice, they had to estimate the cost of a steel frame system alongside their preferred concrete scheme, throughout the design process.[37]

8.8 Simmons Hall interior staircase. Steven Holl Architects and Guy Nordenson and Associates, Simmons Hall at MIT, Cambridge, Massachusetts, 2002.

© Paul Warchol.

8.9 Simmons Hall interior view showing the organic free form atrium interrupting the normative floor-plate construction in a corridor. Note similar incursions exist in some of the dorm rooms. Steven Holl Architects and Guy Nordenson and Associates, Simmons Hall at MIT, Cambridge, Massachusetts, 2002.

© Paul Warchol.

The precast panels (each the size of one dorm room) also facilitated a quicker build process relative to cast-in-place concrete, with one panel attached every 35 minutes.[38]

After the structure was complete, the façade was wrapped in sanded aluminum giving the building a subtle reflectivity, and the window jams and headers were assigned a color. The color pattern was inspired by a graph made by site engineer Amy Stein of the differing diameters of reinforcing steel required at each location.[39] Blue indicates the smallest bars, number fives (approximately ⅝ of an inch in diameter), with green indicating number six bars, yellow number sevens, orange number eights, and red indicating the largest bars, number nines and tens. Thus, along with the filled-in windows, the color-coded façade can be read as map of the forces that carry the buildings' load to the ground.

Simmons Hall opened in 2002 and received considerable praise from architectural critics. Sarah Amelar of the *Architectural Review* noted, "with its cast-concrete exoskeleton clad in sanded aluminum, the chameleon like building changes appearance according to light conditions. Holes in the entry canopy play against the grid's regular rhythm, providing a whimsical rendition of the porosity theme."[40] In *Domus*, Yehuda Safran argues that the project is successful as the social condenser imagined by Holl in his design process:

8.10 Daylight reflecting on a free form opening on the façade at Simmons Hall. Steven Holl Architects and Guy Nordenson and Associates, Simmons Hall at MIT, Cambridge, Massachusetts, 2002.

© Guy Nordenson and Associates.

> If student life is in fact a rehearsal for the future life of civil society, this project can be said to revolutionize everyday life in the university, releasing the ordinary street into a world of experiment and play as an alternative to political apathy and personal isolation. All of 140 meters long and ten stories tall, Simmons Hall is a slice of a city that echoes Holl's own earlier preoccupation with the edge of the city. The relatively wide corridors connecting the rooms turn the hallway into a street-like environment that benefits from the porous morphology in providing unexpected openings, lounges and common halls. These collective spaces are intended to bring students together, to provoke interaction and dialogue.[41]

Raymund Ryan in *Architectural Record* puts the project in the context of Holl's body of work and finds:

> An interplay of opposites has been characteristic of Steven Holl's architecture since his emergence on the New York design scene now a quarter of a century ago. Balancing or intermingling solid and void, opaque and transparent, the rational and the intuitive, Holl has aimed to build buildings with memorable plastic sensibility. For Simmons Hall, the new undergraduate dormitory at the Massachusetts

> Institute of Technology (MIT), Holl infects a perforated, monolithic box with contained spaces that curve and unfold towards natural light.[42]

Simmons Hall's success at resolving structure and enclosure, and crafting an integrated, controlled, and particularized solution to the load conditions and design intentions is emblematic of the successful collaboration between its designers. The long-established relationship and the mutual understanding and respect for each other's talents and goals, led Holl and Nordenson to a remarkable result.

Notes

1 Shlomi Almagor, "Steven Holl's Words, and Edited Selection," Introduction to *Steven Holl and Chris McVoy: 1999–2012, Volume 2* by Yukio Futagawa, Tokyo: A.D.A. Edita, 2012, p. 8.

2 Ibid., p. 10.

3 Steven Holl, Interview by authors, email interview, New York, NY, August 6, 2013.

4 Christopher Platt, "Possibilities of Uncertainty," in *Uneasy Balance*, ed. Christopher Platt and Brian Carter, Glasgow, Scotland: MSA Publications, 2013, p. 43.

5 Shlomi. "Steven Holl's Words," p. 10.

6 Guy Nordenson, Interview by authors, phone interview, New York, NY, June 14, 2013.

7 Steven Holl and Todd Gannon, "Sponge," in *Steven Holl: Simmons Hall*, New York: Princeton Architectural Press, 2004, p. 57.

8 Nina Rappaport, "Guy Nordenson and Associates," in *Support and Resist: Structural Engineers and Design Innovation*, New York: Monacelli Press, 2007, p. 137.

9 Steven Holl and Todd Gannon, "Execution," in *Steven Holl: Simmons Hall*, New York: Princeton Architectural Press, 2004, p. 113.

10 Ibid.

11 Ibid.

12 Nordenson, Interview.

13 Ibid.

14 Ibid.

15 Ibid.

16 Ibid.

17 Ibid.

18 Ibid.

19 Ibid.

20 Adelyn Perez, "Simmons Hall at MIT," ArchDaily, http://www.archdaily.com/65172/simmons-hall-at-mit-steven-holl/ (accessed August 15, 2013).

21 Holl, Interview.

22 Ibid.

23 Yukio Futagawa, "Simmons Hall, Massachusetts Institute of Technology," in *Steven Holl and Chris McVoy: 1999–2012, Volume 2*, Tokyo: A.D.A. Edita, 2012, p. 106.

24 Steven Holl and Todd Gannon, "Master Plan," in *Steven Holl: Simmons Hall*, New York: Princeton Architectural Press, 2004, p. 23.

25 Ibid., p. 58.

26 Futagawa, "Simmons Hall," p. 106.

27 Holl and Gannon, "Sponge," p. 62.

28 Ibid., p. 107.

29 Holl, Interview.

30 Rappaport, "Guy Nordenson and Associates," p. 144.

31 Ibid.

32 Ibid.

33 Steven Holl and Todd Gannon, "Perfcon," in *Steven Holl: Simmons Hall*, New York: Princeton Architectural Press, 2004, p. 71.

34 Steven Holl and Todd Gannon, "Student Rooms," in *Steven Holl: Simmons Hall*, New York: Princeton Architectural Press, 2004, p. 79.

35 Futagawa, "Simmons Hall," p. 107.

36 Holl and Gannon, "Perfcon," p. 73.

37 Ibid.

38 Rappaport, "Guy Nordenson and Associates," p. 142.

39 Ibid., p. 144.

40 Sarah Amelar, "Steven Holl experiments with constructed 'porosity' in his design for SIMMONS HALL, an undergraduate dorm set in the scientific realm of MIT," *Architectural Record*, 191(5) (2003): 204.

41 Yahuda Safran, "Holl's Hall of Residence for MIT is his most Significant Building Yet," *Domus*, 858, April (2003): 40–61.

42 Raymund Ryan, "Kinetic Monolith," *Architectural Review*, 215(1283) (2004): 36–40.

– 9 –

The Anaheim Regional Transportation Intermodal Center (ARTIC)

Design Architect	HOK
Executive Architect	Parsons Brinckerhoff, Los Angeles
Structural Engineer	Thornton Tomasetti, Los Angeles
MEP and Façades Engineering	Buro Happold, Los Angeles
Construction Management	STV, Irvine, CA
Testing and Inspections Consultant	Group Delta Consultants, Irvine, CA
General Contractor	Clark Construction Group LP

The design of ARTIC involved numerous experts and firms, but the discussion focuses on the partnership between HOK and Buro Happold. We begin with the background on the firms.

HOK

HOK is a global design, architecture, engineering and planning firm. Through a network of 24 offices worldwide, HOK provides design excellence and innovation to create places that enrich people's lives and help clients succeed. The firm's thought-leaders create design solutions for clients in 13 strategic practice areas, including aviation and transportation, commercial, corporate, healthcare, and science and technology. In addition to the Anaheim Regional Transportation Intermodal Center in Anaheim, California, HOK's recent transportation projects include the 6.46 million square foot Hamad International Airport Passenger Terminal Complex in Doha, Qatar; PHX Sky Train™ at Phoenix Sky Harbor International Airport in Phoenix; Indira Gandhi International Airport in New Delhi; Indianapolis International Airport in Indianapolis; and the Terminal 5 Automated People Mover at London Heathrow Airport in London.

One of HOK's most ambitious projects to date is the King Abdullah University of Science and Technology (KAUST) campus in Thuwal, Saudi Arabia. The project team—consisting of

300 architects, engineers, interior designers, planners and laboratory design specialists across 11 HOK offices—had less than 30 months to design and construct 5.5 million square feet of complex space across 27 buildings. The project is Saudi Arabia's first Leadership in Energy & Environmental Design (LEED)[1]-certified project and, at the time of its certification, was the world's largest LEED Platinum project.

Sustainability and integrated design are part of HOK's mission, which "is to deliver exceptional design ideas and solutions for our clients through the creative blending of human need, environmental stewardship, value creation, science and art."[2] The firm is consistently ranked as a leader in sustainable design by *DesignIntelligence*. Editor James Cramer explains, "HOK is a firm often cited for making a difference . . . HOK is recognized for breaking new ground with clear, practical and informational leadership. HOK's staff is admired for its compelling case studies, engaging thought-leadership and insights that lead to making wise decisions to benefit the planet's future condition."[3] HOK partners with experts in a wide range of fields, including architecture, interior design, engineering, planning and urban design "to research alternatives, share knowledge and imagine new ways to solve the challenges of the built environment,"[4] all of which are demonstrated in the following case study.

Buro Happold

Buro Happold is one of the go-to engineering firms for architects and clients seeking creativity, holistic integration and constructability in design. Widely viewed as innovators in the industry, Buro Happold was founded in 1976 by Ted Happold and today the firm employs 1,400 people with a wide range of expertise in 29 offices around the world. The Los Angeles office was founded in 2006 by Greg Otto, who was educated as both an architect and engineer and believes strongly in collaborative modes of practice. Otto explains his approach to developing a robust team:

> We do engineering quite a bit differently, we think differently about it . . . so we have to do [hiring] organically . . . It's challenging to nurture the ethos necessary to do this type of work, which is between disciplines: it's engineering, but not pure engineering, it's architecture, but not pure architecture. It's the middle ground, which is a challenge for engineers and architects to walk into . . . We look for people that are gung-ho to take responsibility, take a bit of risk and challenge convention.[5]

The Los Angeles office works at a range of scales from installations to mega structures. Buro Happold Los Angeles completed structural and MEP engineering for the award-winning Helios House, a fully sustainable, prefabricated BP gas station designed by Office dA and Johnston Marklee, completed in 2007. At the opposite end of scale, one of the largest projects for the Los Angeles office to date is San Francisco's Transbay Transit Center, scheduled to be completed in 2017. The firm provided sustainability and MEP engineering with architectural design by Pelli Clarke Pelli. Similar consulting services were delivered for the Perot Museum of Nature and Science in Dallas designed by Morphosis, which employs, among a multitude of other green infrastructures, a 100 percent gray water capture system for reuse in the building. The sustainable measures in the museum contributed to an award of Four Globes, the highest rating issued by the Green Building Initiative. Buro Happold continually receives international praise for design innovation while furthering the engineering fields. Their research-oriented approach is exemplified in the following case study.

The ARTIC Project

The Anaheim Regional Transportation Intermodal Center (ARTIC) is a new 67,000 square foot terminal providing connections for ten different modes of transportation as well as support programs including commercial tenant and dining space, ticketing, lobby and operation offices. The intermodal station will serve the Orange County Transportation Authority (OCTA), Metrolink, AMTRAK, local shuttles and buses, international buses, pedestrians and bikers, taxis, and parking for 1,082 vehicles. High-speed rail and light rail may be connected in the future. The allocated $184 million budget is funded through county, state and federal government transportation support measures.

ARTIC is located on the north side of the Anaheim Angels Stadium parking lot, a short distance from Honda Stadium, and will provide easy public transportation access to the sports arenas and the vicinity while serving as a hub for Anaheim's numerous tourist destinations including Disneyland. More than 40 million tourists visit Anaheim annually, generating $8.7

9.1 The Anaheim Regional Transportation Intermodal Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

© HOK.

9.2 Interior view showing the direct and simple circulation. The Anaheim Regional Transportation Intermodal Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

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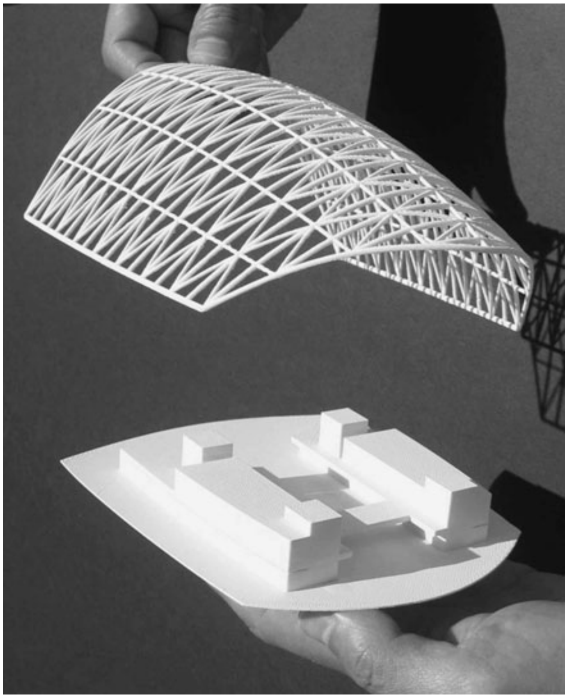
billion in revenue and creating thousands of jobs for the city, which is the tenth-largest in California. The city is projected to grow 13 percent by 2035, which will put added strain on the county's already congested roadways, a huge motivation for building the intermodal station.

As stated in the Request for Proposals (RFP), the City envisioned that "ARTIC will be a showcase transportation center and sustainable throughout, creating a lasting civic facility and regional gateway to Orange County." Hundreds of firms responded to the RFP and the Parsons Brinckerhoff (PB)/HOK team was awarded the contract in 2009, beating out such world-renowned designers as Gehry Partners, Pelli Clarke Pelli, Foster + Partners and Santiago Calatrava. It was an extremely fast-tracked design process. The initial proposals from PB/HOK reflected both firms' design heritage, which include numerous airports and other transportation facilities. The team's proposals were firmly committed to the LEED platinum goals. Arnold Lee, Senior Project Designer for HOK, says that, "Because of the unique shape of the proposal, we did multiple schemes: one was a more traditional repeating bay structure, which you would associate with large infrastructure projects; it was very rational and allowed for flexibility. But the one the client chose was a big soaring design that is very iconic and specific,"[6] and fulfilled the city's vision for an intermodal hub that would not only support public transportation growth, but also spark commercial development in the region.

This case study demonstrates a different kind of collaborative mode from some of the others featured in the book. In this project, the complexity and scale of the design and execution



9.3 Shell geometry demonstrated in a 3D print. The Anaheim Regional Transportation Intermodal Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

© HOK.

required a very diverse skill set—a matrix of experts. During design development, Eric Anderson, Senior Project Manager from PB Architecture, oversaw the PB/HOK collaboration which included design and engineering for the rail infrastructure, traffic planning and intermodal design. About six months before the bid process, Virginia Tanzmann, FAIA, Architect and Vice President of PB Architecture, took on management of the project and the 20-plus consultants. Clearly, the collaboration between HOK and Buro Happold showcased below represents a snapshot of the coordination required to realize ARTIC. The work pushed the boundaries of traditional architectural and engineering practice; the players wore multiple hats during the design process, crossed disciplines and faced responsibilities outside of the “normal” call of duty. With computation tools becoming at once more accessible, but also more intricate, the expertise required to execute complex projects efficiently and cost-effectively is very specialized and specific. At the same time, the designers interviewed for the book all reflected the fact that the project would not have been possible without the collaboration (and cooperation) of the interdisciplinary team.

The Project Team

ACHIEVING the project goals within budget was the feat of a large group of designers and technical experts. Tanzmann remarks, “This is my 40th year as a licensed architect and this is the most exciting project I've worked on—a culmination of so many things. Every system in it is wonderful and to accomplish that with success requires successful collaboration . . . It's extremely complex, but that's part of the fun."[7] The scale, scope, projected use and timeline of the project were hugely demanding; add the uniqueness of the design that uses entirely customized systems and the sum total is one of the most complex projects in contemporary practice.

The initial design proposals were developed by a team composed of architects, planners, landscape architects and engineers from PB and HOK, structural engineers and façade consultants from Thornton Tomasetti along with mechanical engineers at Buro Happold. Lee describes that,

> as a transportation facility, these kinds of projects have very long life spans, especially with this size of terminal station, so there had to be a careful balance of longevity and permanence that you associate with large infrastructure projects, but at the same time, there were financial and time constraints on the project . . . It was a very complex job, so for us, the most important thing was to make sure we had a healthy collaboration with structural enclosure, mechanical, sustainability, which were all front and center from the very beginning.[8]

After the client approved the scheme, the team shifted to developing the project. Given the complexity and invention required for the façade systems and the tremendous risk involved (including cost and life safety), it was essential for the widely varied team of experts to rationalize the systems and test them virtually. Lee describes the shift in the design team responsibilities: "Thornton Tomasetti is an excellent firm and they did the structural enclosure. Buro Happold was doing the mechanical, which is of course really important for a highly sustainable building. Due to the difficult and challenging geometries of the project we realized it was helpful to have all the complex geometry, MEP and enclosure all under one roof."[9] Given that Buro Happold was deeply involved with the enclosure already, their team's responsibility was expanded to develop and optimize the façade systems.

Lee explains the selection of Buro Happold: "[They are] engineers who have the history, track record and ability to start very, very complex projects where the solutions either weren't readily available or are not conventional market solutions, and we worked together towards designing these solutions. Since it is a small office, they ramped up their staff, wrote their own software and were able to juggle between different kinds of complex programs to get us the right solution. Plus they had resources to tap worldwide. It worked out great."[10] Greg Otto describes the Buro Happold team that worked on the ARTIC project: "On complex projects, you really have to have both sides of the equation. Sanjeev [Tankha] is an architect by training, Kurt [Komraus] has worked for an architect for the bulk of his career; Steve Lewis is a pure engineer. That's the way this practice needs to be to do this type of work . . . Cross-disciplinary boundaries really matter to this project,"[11] which was designed as an almost entirely customized enclosure.

Defining the Form, Structure and Materiality

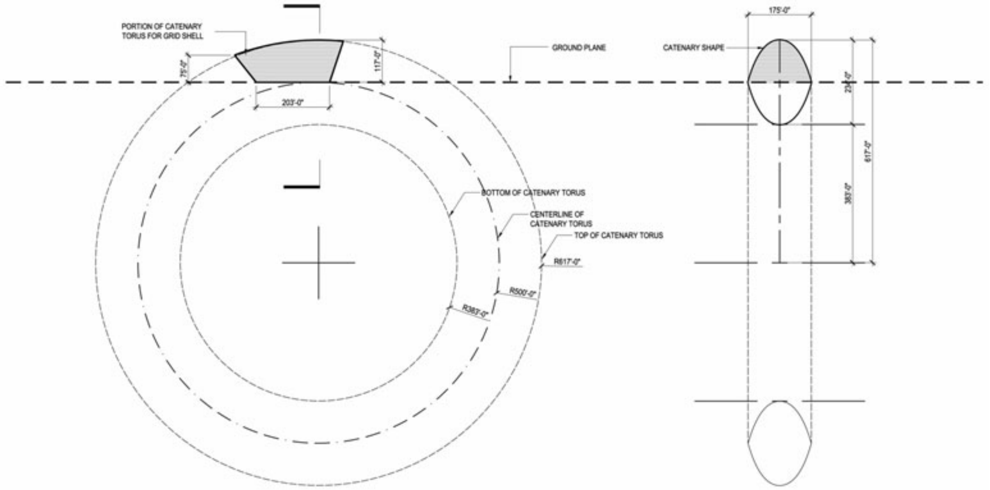
The original competition-winning design was inspired by iconic infrastructure projects, including two that are both now demolished, Broad Street Station in Philadelphia and New York City's Penn Station. Both historical projects demonstrate the dynamic effects of a glass and steel shed with free circulation and loads of natural light. These historic influences and the ARTIC project goals led to the design of a long-span, gridshell structure to create a grand, naturally lit space that allows for open circulation, crucial on stadium event days when there will be surges upwards of 50,000 people. The design team focused on efficient, parabolic shell geometry through the design of a catenary curve swept on a torus.

9.4 Penn Station, Interior, Manhattan 1935.

© Abbot Bernice 1898–1991 (New York Public Library).

9.5 The grand lobby will be enclosed by a soaring grid shell composed of steel and frit patterned ETFE pillows to mitigate heat. The Anaheim Regional Transportation Intermodal Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

© HOK.



9.6 The geometry of a parabola swept on a torus enables a very efficient and light structure. The Anaheim Regional Transportation International Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

© HOK.

The original competition-winning design had a height of 180 feet, which was reduced to a height of 120 feet for the bid package. According to Lee,

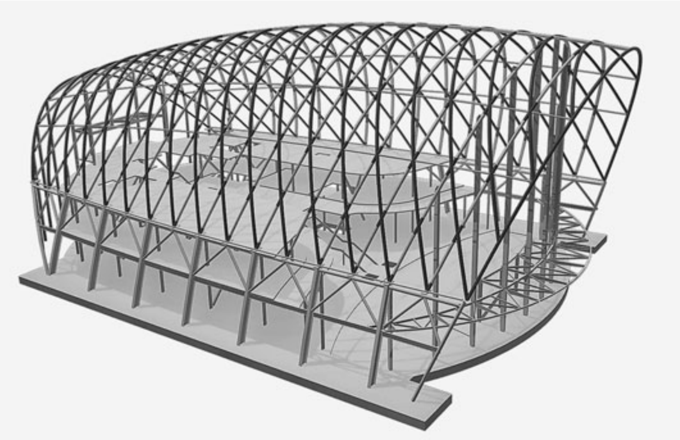
> Since it was a competition, it was challenging because you don't get to speak to the client. Once we started the project, we found out more about the site and about the political and economic conditions that were shaping the project, we realized that we had to adapt the scheme almost immediately . . . It was really a challenging kick-off to the project.[12]

The interdisciplinary team worked through numerous options to maximize the design for aesthetic ambition balanced with efficiency requirements and constructability goals.

Early on, the soil tests indicated that the level of backfill (uncompacted soil that was not native to the site) would require extremely robust foundations, which would demand a disproportionately large chunk of the budget for the site work and concrete:

> So that immediate pressure triggered an investigation into a very lightweight material to reduce the foundations . . . Because of the economic pressures, we had to come up with something that could be built relatively quickly, efficiently, lighter, cheaper, etc. so we started looking at long-span structures to reduce the amount of steel. We looked at efficient shell structures to lighten the weight of the roof and we looked at alternative membrane structures because the foundations were just going to be too big, so ETFE was one of those solutions.[13]

David Herd, Managing Partner for Buro Happold North America, led the MEP team and helped to push forward ethylene tetrafluoroethylene (ETFE) on the project. ETFE is a very lightweight translucent plastic that when assembled in multi-layered panels is used as a highly energy-efficient façade component, particularly in roofs. Since ETFE is 1/100th the weight of glass, the



9.7 The use of ETFE, which is 1% the weight of glass, enables the reduction in steel. The Anaheim Regional Transportation International Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

© HOK/Buro Happold.

material was key to enabling lighter foundations and reduced costs. It also factors into the project's LEED certification since the material is responsibly manufactured, helps lighten the load (thereby reducing emissions) during transport to the site, provides excellent insulation for temperature regulation and is recyclable. ARTIC is currently the largest ETFE project in North America with the material covering 200,000 square feet of roof surface. Engineers at Buro Happold worked closely with their colleagues throughout the world as well as the material fabricators to hone the details to insure constructability of the system. Incidentally, Ted Happold was the first designer to introduce ETFE as a cladding material and it was used to skin the Mannheim Multihalle gridshell that he designed with Frei Otto (while Ted Happold was still working with Arup) and completed in 1975. Given Buro Happold's long and intimate history with the material, the ARTIC team was able to draw on three generations of knowledge of manufacturing, construction and performance.

Rationalizing the Façade Systems

In addition to the ETFE roof, the other major façade systems at work in ARTIC include two parabolic glass walls at the front and back of the building as well as metal panel walls that enclose the sides of the structure. Each of these systems went through rigorous rationalization, "optioneering" (evaluating multiple design options) and constructability assessments. Computation experts at Buro Happold created customized software and also used CATIA, Grasshopper, Excel, Robot and other analysis software to assess aesthetics and performance of the systems. Because of the fast project schedule, the team at Buro Happold was given six weeks to optimize the façade systems and provide a model in Revit, which was required by the client and enabled a 3D model of the project to be shared among the various architecture and engineering offices.

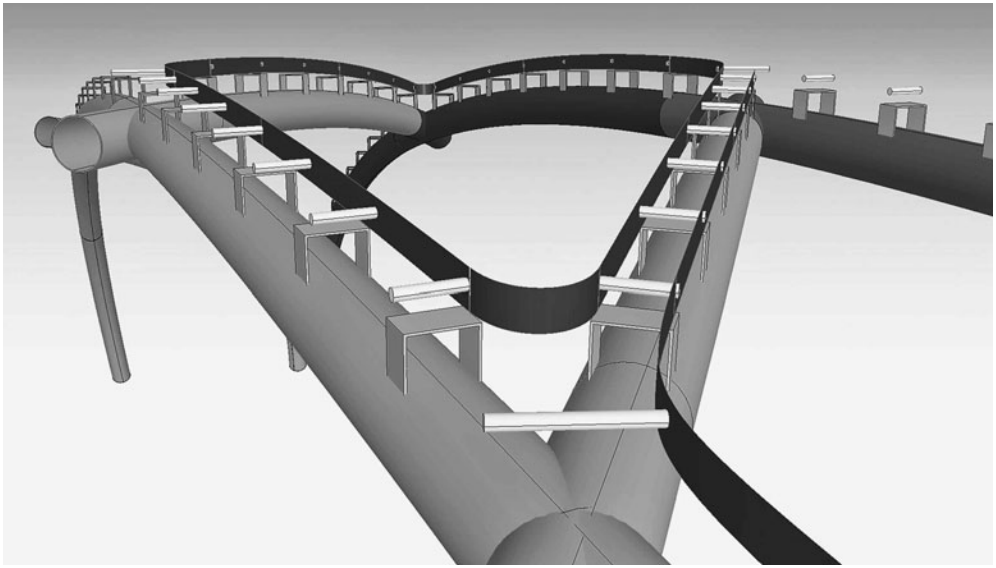
Ian Keough, senior technical designer, wrote software that helped the team generate the initial geometry. Through scripting and evaluation of the systems, the Buro Happold team reduced the depth of the structure by about a foot from the original scheme. Kurt Komraus of Buro Happold essentially became part of HOK's design team and worked almost every day in their office, which is across the street from Buro Happold's Culver City location. Komraus, an Associate, worked to define the prime geometry utilizing CATIA and custom scripts to create a constructible system. The "Geo Grid," as it came to be called by the team and contractors, was modeled in 3D and exported into a 35-page spreadsheet that defined each of the x-y-z coordinates for the bid package. Buro Happold maintained several models in various softwares, each providing a different strategic purpose in design development. The prime geometry was articulated in CATIA and the Revit model was created to interface with HOK's interior model.

The rationalization process for the structure and façade was both intricate and multifaceted. Buro Happold used Thorton Tomasetti's structural geometry communicated through node identifications, which is industry standard. The Buro Happold team incorporated the primary geometry from Thornton Tomasetti into every analytical model that was created. Sanjeev Tankha, Associate Principal at Buro Happold, describes the process:

> There is an inherent efficiency in analyzing the whole system and the interactions of the various components down to the details. Especially in this project where we had to drive budget down and take as much fear out of the budget as we could, we had to analyze everything, which has an element of redundancy. Systems are a lot more efficient if you analyze them holistically.[14]

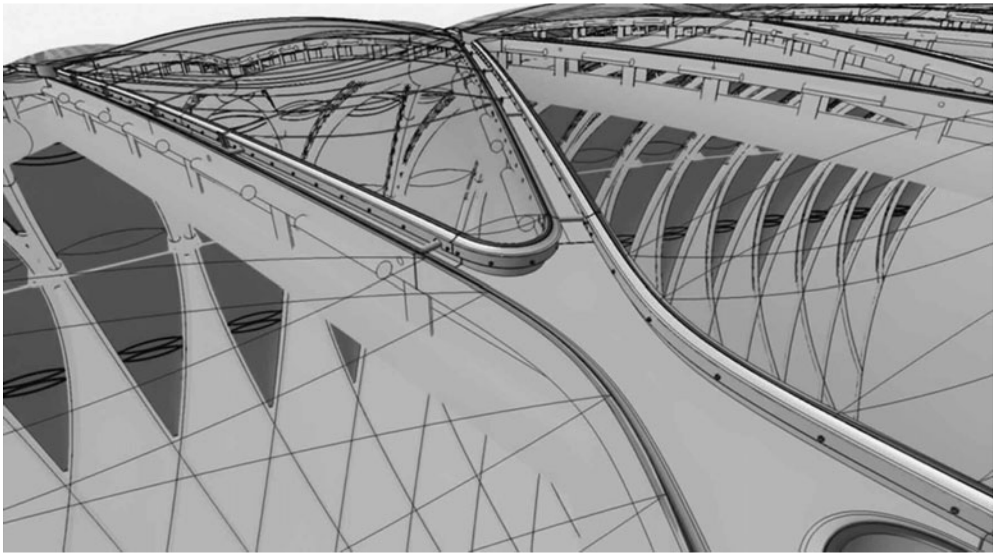
Given that each façade node needed to be normal to the surface, which was a form defined by HOK, each component of the structural anchorage, steel plates and ETFE support channels was defined and modeled in order to evaluate the design. There are 3,000 stools that support the channel extrusions that anchor the ETFE and each of these required a placement in space deciphered through a detailed CATIA model. Komraus scripted the design of the componentry to adjust to the different angles and heights of plates needed to support the diamond-shaped cushions. Every time an adjustment was made to the form or materiality, the scripts were modified to generate new placements. This process is facilitated through parametric software and expert skill sets, but can take months when modeling in traditional CAD programs.

A number of factors played into the decision making for the ETFE façade system. Firstly, with constructability and aesthetics in mind, Buro Happold oriented the stools normal to design surface to limit the stools to only one type to support the ETFE foils. Each stool is a developable



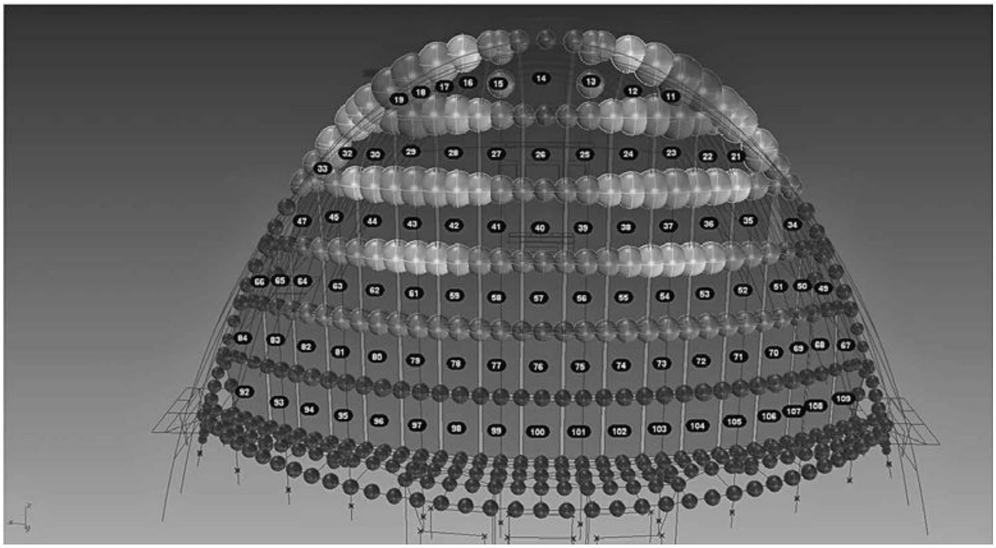
9.8 ETFE Pillow System. The Anaheim Regional Transportation International Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

Drawing courtesy of Buro Happold.



9.9 All of the ETFE framing components were modelled to analyze the system. The Anaheim Regional Transportation International Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

Drawing courtesy of Buro Happold.



9.10 Grasshopper model to visualize the bubble deflection magnitudes. The Anaheim Regional Transportation International Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

Drawing courtesy of Buro Happold.

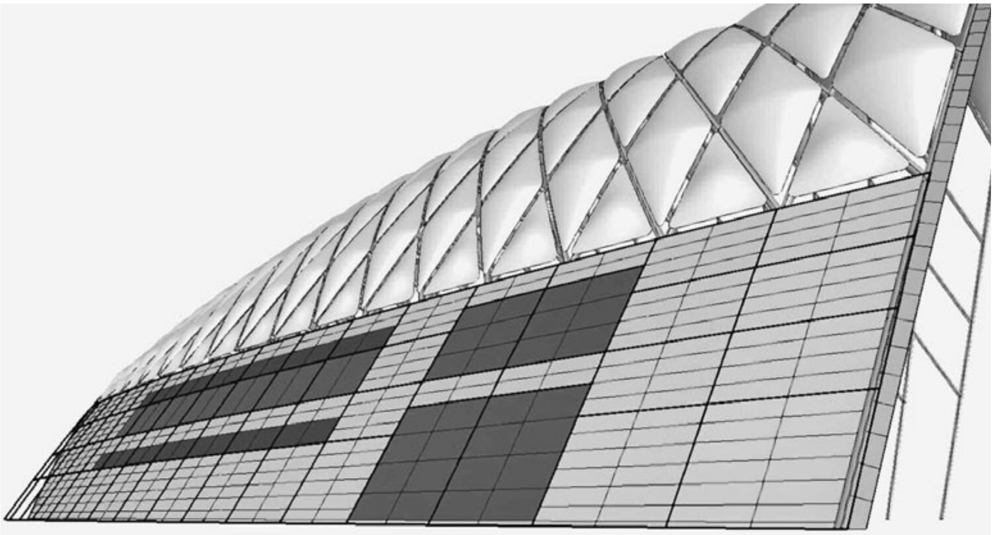
plate, allowing for ease of fabrication through waterjet cutting. Buro Happold was also striving for elegance in the design and worked to reduce the size of the clamps, which have a significant impact on the visual perception of lightness and buoyancy. Wind loads were also a huge factor in developing the detailing since the largest foil is an unprecedented 88-foot length. Stephen Lewis, Associate and Senior Engineer, developed a Grasshopper model to visualize the bubble deflection magnitudes and as a result, the team modified the detailing to include slip cables to restrain the cushions and reduce stress on the structural frame during high wind. Lewis describes the system: "In essence there are three key cushions over the surface of the structure and these cushions had to be form-found . . . We analyzed the cushions and looked at maximum stresses; if those were exceeded we modified the shape through another process of form-finding and added the slip cables."[15] Each cushion is composed of three layers of foil that create an impressive insulating enclosure that can achieve a U value of 1.96 w/m^2°K. The material filters infrared light and has an added frit pattern on the outer layer that reduces solar heat gain while allowing light penetration, further enhancing the sustainability measures that contribute to the LEED platinum goals.

The secondary structural system for the façade was closely coordinated with Thornton Tomasetti's primary structural system. With wind and seismic loads, there will be moments of large deflection in the systems, which needed to be flexible enough to move together. Lewis describes that design process, saying that they "developed scripts in Grasshopper to process that data, describe it visually and used it to inform detailing to accommodate movement. We had 30 load cases from Thornton Tomasetti that we had to process."[16] That information was then integrated with the CATIA wire frame model, moved through Grasshopper and analyzed using Robot.

A similar holistic approach was taken in the design of the faceted end walls, also a customized structural system. The geometry, 120 feet tall at the highest point, was defined by HOK then Buro Happold ran through multiple options to assess the aesthetic effects and costs of various systems. Komraus says, "That was a big piece of geometric rationalization that directly affected the design. I sat with the designers and parametric models and said, well, if the glass panels are this size then it will interface with the diagrid this way . . . You can see the geometry come together in a rational way, but there were so many decisions that had to be made with the architects and engineers concurrently."[17] The team settled on a cable hung system to echo the roof condition and reinforce the lightweight quality of the enclosure.

Tankha explains, "We conducted a series of studies within the price point for the wall system. Given the aesthetics that the architect wanted to see, we went through an 'optioneering' process (engineering options for the curtain wall system as opposed to value engineering because you want to keep the value). We actually arrived at a system that was very close to the original aesthetic,"[18] and maintained the allowed budget for the system. When describing the "optioneering" process the team went through, Tankha says,

> I think it's a collaborative process and it [happened] over a series of nine months where the geometry was defined and the architects' aesthetic goals were laid on the



9.11 The team eliminated customized forming of individual panels. The Anaheim Regional Transportation Intermodal Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

Drawing courtesy of Buro Happold.

> table. You start with a system and loop it through budgeting, talking to contractors, talking to the industry and tweaking the systems. We aren't working in isolation; we are working in tandem with the industry so all the feedback from them is looped back into the engineering. That's critical to working today. Working in a vacuum never helps.[19]

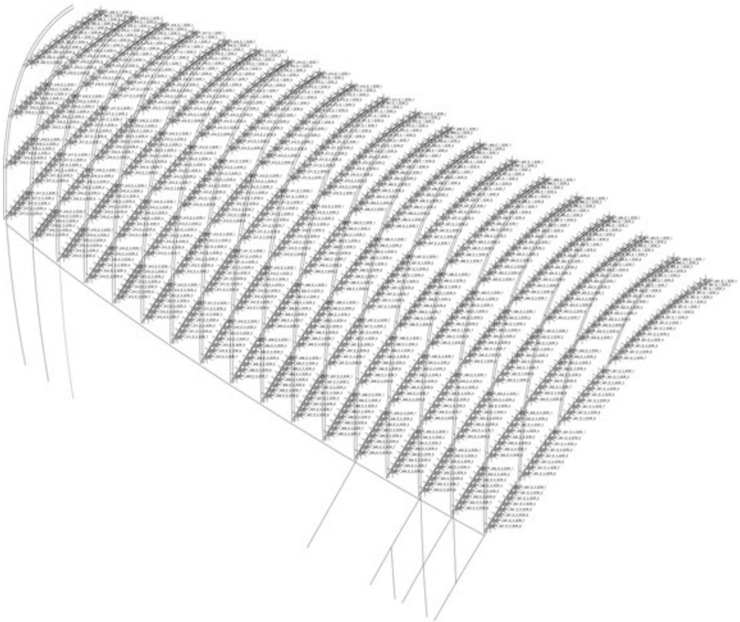
The side walls also required a great deal of computation and rationalization. Komraus and the team worked to reduce the wall from more than 400 unique panel types to about 50. Given the curvature of the wall as a whole, there was an effort to eliminate customized forming of individual panels and so the geometry was defined as a series of planes formed by a translated polyline. The subdivisions, composed of 8 to 12 identical panels, are planar parallelograms. This process was hugely significant in reducing costs—the ETFE and structure were mostly fixed, but the panels' portion of the budget was significantly reduced through the rationalization process. Tankha describes that, "During the design process, there was back and forth with suppliers and subcontractors. Once the geometry panelization was set, we drove in on the detailing. Normally an engineer wouldn't go down to this level of detail in a model, but we wanted to make the system very clearly defined and transparent to get a realistic bid."[20]

The systems were rationalized in CATIA with a series of customized scripts, analyzed in Robot and then imported into Revit for documentation for the enclosure drawing set, which was a collaboration with HOK on the detailing. All the dimensions were removed from the architectural drawings in order to make the geometry set the prime reference point for construction. Komraus wrote a visual key to enable the definition to be easily understood by the contractors. Thousands of points in space are identified in both drawing and spreadsheet form. Although these drawings may have initially scared off some contractors from bidding on the project, the contractors embraced the team's method of relaying information, and Tankha says that the Geo Grid "has been really successful with contractors. They are all on board."[21]

Bidding Process and Construction

With complex projects at the scale of ARTIC, risk plays a huge factor in the decision-making process. Through careful research, modeling and testing, the design team produced a bid set on time and on budget. Otto explains that, "At the end of the day, if a design is not commercially intelligent then you have to ask yourself why . . . We took something incredibly complex and explained it and simplified it so that others could understand it so that various players could make a good bid and the client could get good value."[22] Tankha agrees, saying that, "Technology is only here to make life easier, and if you keep it complicated, then it won't be buildable."[23]

Tanzmann, PB Project Manager, describes that, "We had a contractual obligation to bring this in on budget so we had a cost estimating firm as part of the team and we spent serious time



9.12 A portion of the Geo Grid. The Anaheim Regional Transportation Intermodal Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

Drawing courtesy of Buro Happold.

beating up on the design to figure out how to build this fabulous design on budget—not easy to do with a building as unique as this one. It's got systems that are at the cutting edge and hard to estimate and the geometry is highly sophisticated . . . Part of my job is getting the design in control budget-wise. I brought everyone into a room and we looked over the pros and cons of different kinds of adjustments. At the end of the day, we succeeded: the bids came in great."[24] The city of Anaheim defines a Successful Bidder as the "lowest qualified, responsive and responsible bidder." Of the eight contractors that responded, six were within $1 million of each other on the estimated $125 million project. The low bid by Clark Construction Group LP of $126 million was selected.

In general, in the United States and elsewhere, state-supported projects are publically accountable and must adhere to strict rules that enable a competitive bidding process. Building Information Modeling (BIM) is now required as a deliverable for many state agency-sponsored contracts. In the case of ARTIC, the team was obligated to deliver a Revit model, although the bid set was still paper-based and included the drawing set as well as the 35-page spreadsheet defining the Geo Grid of x-y-z coordinates. Komraus describes that during the bid process, "the question would come up, 'Is this a tolerance?' It's not a tolerance, it's a definition. If you were looking at the computer, there'd be a lot more decimals on each number."[25] It's hopeful that more government-sponsored projects will be communicated through 3D information, rather than strictly 2D drawing sets. Given the complexity of ARTIC, the contractors now use BIM models because it's the only way to understand the systems.

On September 18, 2012, just one month after the general contractor was selected, a ceremony was held to break ground, and the project is expected to be completed in 2015. The design team worked with fabricators to generate mock-ups for each of the façade types. The diagrid system is being manufactured by Gartner in Chicago. Gartner's German plant manufactured the façade for Coop Himmelb(l)au's BMW Welt and helped to advise their Chicago colleagues in fabricating the roof façade system and to refine detailing for ease of installation. One-to-one prototypes of the ETFE modules enabled the team to assess light qualities for daylighting and an adhered RGB LED system that will line each cushion.

Tanzmann describes the first nine months of the planned 26-month construction schedule:

> There's a tremendous amount of site work to do because we need to retain water that's developed on the site. There are storm water reservoirs to hold excess water, grading, landscape, paving, roadwork, signalized sections—we are changing the streets—traffic management work, a railroad bridge had to be redesigned and replaced . . . It's really complex . . . Of course, in the early stage there's a huge amount of submittals. This particular site has soil issues so they did deep dynamic compaction—an 80ft crane dropped a huge weight to compact the soil. Not so long afterwards they were able to pour the slab—a rigid plane that floats so that it won't crack . . . The steel framing for the interior has gone up and they're putting on the decking because it's three levels high. The pressurized ETFE has just started to go up as well as the framing for the elevators and escalators. So right now construction

9.13 Envisioned as a catalyst for growth, a central spine unites the site along pedestrian axis from Honda Center, through the Station, then onto Anaheim Stadium. The Anaheim Regional Transportation Intermodal Center (ARTIC), PB/HOK, Buro Happold, Anaheim, California, 2014.

© HOK.

> is technically scheduled through end of 2015, but the contractor is running slightly ahead of schedule.[26]

Since the building was not completed at the time of writing, the story of ARTIC's realization is not yet concluded. However, it is clear from the team's achievements in cost-effectiveness and scheduling that there were a multitude of triumphs in the design process. The project is on target for LEED platinum status and will likely spark Transit Oriented Development (TOD) in the vicinity. Tankha comments that, "One of the successes of this project was HOK saying, let's collaborate and do this as a team as opposed to trying to drive the whole thing on their own."[27] Greg Otto agrees, saying,

> It's not an easy building. The world is now so complex—it's beyond an individual. The notion of the Beaux Arts architect with his cape and beret barking orders is an

> obsolete model. There are a lot of experts at the table and the challenge is how you get them to come together. Obviously, the digital prototype is probably the best because it's the way you get all that knowledge mashed up into something that forces collaboration and coordination. But being able to communicate with other people is key . . . In order to do this project right, you really had to have a view about what great design is, the total value for the project and how to achieve it. So it was the cross-disciplinary boundaries that mattered . . . You have to be bigger than your own silo.[28]

Notes

1 LEED is an environmental ratings system officiated by the U.S. Green Building Council.
2 http://www.hok.com/about/ (accessed March 18, 2014).
3 http://www.hok.com/about/sustainability/ (accessed March 18, 2014).
4 http://www.hok.com/about/ (accessed March 18, 2014).
5 Greg Otto, Interview by authors, in-person interview, Los Angeles, CA, June 12, 2013.
6 Arnold Lee, Interview by authors, phone interview, San Francisco, CA, May 30, 2013.
7 Virginia Tanzmann, Interview by authors, phone interview, July 31, 2013.
8 Lee, Interview.
9 Ibid.
10 Ibid.
11 Otto, Interview.
12 Lee, Interview.
13 Ibid.
14 Sanjeev Tankha, Interview by authors, in-person interview, Los Angeles, CA, June 12, 2013.
15 Stephen Lewis, Interview by authors, in-person interview, Los Angeles, CA, June 12, 2013.
16 Ibid.
17 Kurt Komraus, Interview by authors, in-person interview, Los Angeles, CA, June 12, 2013.
18 Tankha, Interview.
19 Ibid.
20 Ibid.
21 Ibid.
22 Otto, Interview.
23 Tankha, Interview.
24 Tanzmann, Interview.
25 Komraus, Interview.
26 Tanzmann, Interview.
27 Tankha, Interview.
28 Otto, Interview.

– 10 –

SPG Shanghai

Architects	SOM: Craig Hartman, Ben Mickus and Alessandro Rozza
Structural Engineers	SOM: Mark Sarkisian and Eric Long
Graphic Design	SOM: Lonny Israel
Sustainability Consultants	WSP|Flack and Kurtz

The SPG Shanghai Project is an unbuilt competition design created by engineers and architects working at the firm of SOM. This case study looks at the collaboration between professionals with different disciplinary backgrounds within the same organization and the role of competitions in interdisciplinary collaboration.

SOM

SOM occupies a unique place in contemporary and historical structural engineering and architecture in the United States. Founded by two architects, Louis Skidmore and Nathaniel Owings, and an engineer, John Merrill, it is best known for designing and building high-end commercial buildings, particularly tall buildings. Two early figures in the firm's history who exemplify the innovative collaboration between structural engineers and architects, for which SOM has become known, are Fazlur Khan and Bruce Graham. Together they designed some of the world's most innovative and groundbreaking skyscrapers, and were a significant part of the movement referred to as the Second Chicago School of Architecture. Their use and refinement of the tube structural system pushed tall buildings ever higher, making them more user-friendly by eliminating many of the interior columns that earlier skyscrapers such as the Empire State and Chrysler buildings had in abundance. Graham and Kahn's designs display remarkable structural expression; the structures "were closely integrated with the architecture and, in many cases, became the architecture."[1] Perhaps their most famous collaborations were the John Hancock Center and the Sears Tower (renamed the Willis Tower), both in Chicago;

the latter was the tallest building in the world for decades after its completion. These buildings set the standard for tall building construction for years to come. Significant contemporary projects include the Burj Khalifa in Dubai (currently the tallest structure in the world), the Jin Mao Tower in Shanghai, One World Trade Center in collaboration with architect Daniel Libeskind, and the Cathedral of Christ the Light in Oakland California.

The Collaboration

Craig Hartman, design partner in SOM's San Francisco office and lead architect on the project, describes SOM's practice as "fundamentally interdisciplinary." In addition to architecture and engineering services, the firm also engages in urban design, interior architecture, product design, and graphic design. As such, Hartman emphasizes that a culture of collaboration is of primary importance to the success of the firm: "Specifically in architecture and structural engineering, it's very important for the collaborative environment to exist for this work. The firm's history has been defined by that for the last 50 or 60 years."[2] Hartman further describes the firm as engaged at every level in design for the city. With ever-increasing urbanization of the world's population, he argues that the twenty-first-century challenges and opportunities that engineers and architects will have to address will be: the capacity of cities to simultaneously expand while dealing with resource depletion, scarcity of resources relative to increasing population, the resulting climate change, and the attendant social and political issues that will emerge. Resolving these complex strands is inherently an interdisciplinary problem. "Cities are absolutely the focus of our practice and that practice is absolutely interdisciplinary."

Speaking about the way physical proximity and the capacity to meet internally are facets of successful collaboration between architects and engineers at SOM, Hartman asserts that the culture of collaboration within an organization may be more important than any other aspect:

> I have to say the most important thing of all: you can have all the communication tools you want, you can be sitting next to one another, but unless there is a culture that reinforces, and in fact demands this approach to work, it won't happen. So the culture here in this particular practice is extremely focused on trying to find ways to use all of the design disciplines as powerfully as possible.

Hartman credits the long-standing culture of collaboration at SOM as the primary factor driving the way structure and architecture are integrated by the firm:

> For the most part the design partners and directors who lead the practice of SOM have come up through the firm. Almost all of the partners, all of the directors are

> people who have spent almost their entire careers at SOM. There's a cultural bias toward the idea that structure and form are very related ideas. There's an aspiration, an underlying ethos that suggests that the way things are is the way they look. When you make a building, we believe that the physical facts of the building are part of its expression. That's not to say every nut and bolt needs to be expressed, but simply that the reality of making a tall building or a long horizontal building stand up, the way those things work are part of the architectural expression. Obviously the last decade there's been a lot of focus on the idea of sculpturalism and in many ways that is as ephemeral an idea or as fleeting an idea as the various other -isms of the last fifty years: of deconstructivism, postmodernism, you name it. We're trying to find an authentic means of expression and that's where this idea of structure in architecture comes together in a very fundamental way. It really is cultural here at SOM.

Ben Mickus, an Associate and architect, adds that the way the different designers share digital information is also as important as verbal communication:

> If there's a digital model that the architects develop, we pass that over to the structural engineering group, they do their analysis. Based on the results of that analysis they come back to us perhaps with a revised model or we make revisions to the model based on what they found. So there's a back and forth, a loop of digital communication in addition to the verbal communication.[3]

Mark Sarkisian, Structural Engineering Partner, argues that it is imperative that engineers come into the design process ready to innovate and willing to contribute the big ideas: "I think otherwise don't come to the table. Don't be involved."[4]

The Project

THE project, which was designed in 2010, is a large urban block in a rapidly developing part of Shanghai and was designed as part of developer SPG's bid to buy the land from the Chinese government. China has undergone massive urbanization in the past 15 years and the government plans to continue this process over the next 15 years. The migration associated with this urbanization is a huge cultural shift for those formerly rural inhabitants. To accommodate all these new urban citizens, very large-scale and very rapid development has taken place in quite a planned way. The integrated nature and large scale of the planning is possible in China in a way that it would not be in any Western country because the Chinese government owns virtually all of the land. The procedure associated with the ongoing development that has emerged is such that the government has undertaken master planning for new cities and new districts adjacent to existing cities, and marked specific areas for development of transportation facilities, business districts, residential zones, and so on. From those master plans, individual development blocks are identified and real estate developers then bid to purchase them by proposing designs that meet the objectives set out in the master plan. Generally the highest bidder wins the rights to develop, but the quality of the proposal is also taken into account. The money from the sale of the land is then reinvested in urban infrastructure.

The site for the SPG Shanghai project is in Hongqiao CBD, which is adjacent to the original international airport in Shanghai. With the building of a new larger international airport, it was decided that the older airport would become a domestic airport and the land around it would be developed into an intermodal transit hub encompassing air travel, buses, high-speed rail, local commuter rail, subways and private vehicles. Alongside this would be a new central business district and associated residential zones. The site for the project is adjacent to a river and consists of two development blocks from the master plan.

10.1 Map of the master plan. The site is labeled D13 and D23 and the intermodal transit hub can be seen in the center of the image. SPG Shanghai, SOM, Shanghai, China, 2010.

© SOM.

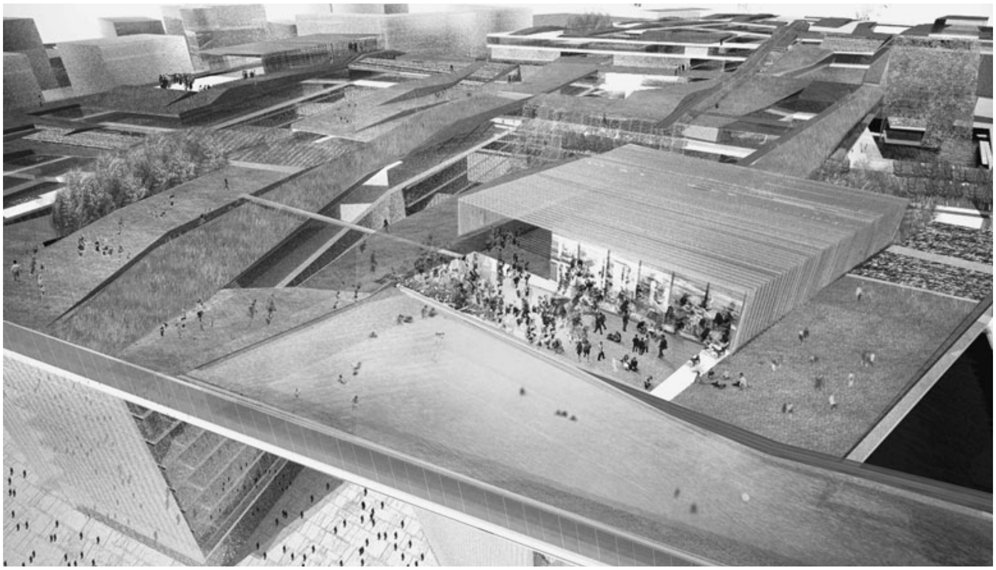
There were a number of design challenges inherent in this project for the designers at SOM. The first has to do with the scale of the development. The two blocks of the master plan would be the size of eight or more city blocks in a US city. Hartman notes that Chinese planning policy is to have large-scale blocks with very large-scale streets that separate them. He argues that these blocks tend to end up as islands that feel privatized and lacking in a sense of urban connectedness.[5]

SOM is currently engaged in a number of large-scale projects in China, and in all of them this issue is one they strive to address. "We try to make these projects catalysts for greater porosity in their surrounding environments and thus greater connectivity."[6] Environmental concerns were also front and center in the design process, both in terms of minimizing the impact of the project's energy and water consumption, and in terms of mitigating some of the existing environmental issues on the site, primarily air pollution and noise pollution. The other significant challenge was the transportation system and its integration into the project. The designers at SOM felt that the master plan did not adequately address the transportation connectivity between the transportation hub and the new CBD, resulting in inefficiencies and necessitating long detours for private cars in particular. Together the architects and engineers at SOM set out to design a project that would address each of these concerns.

The proposal has a series of eight- to nine-story-high buildings that maximize the developable area within the height restrictions, enabling the design of an expansive green space

10.2 Schematic design: A series of mixed-use buildings, eight or nine stories high, with retail and entertainment on the ground and below ground levels. The expansive roof deck that spans across the open space between buildings ties the buildings together. SPG Shanghai, SOM, Shanghai, China, 2010.

© SOM.



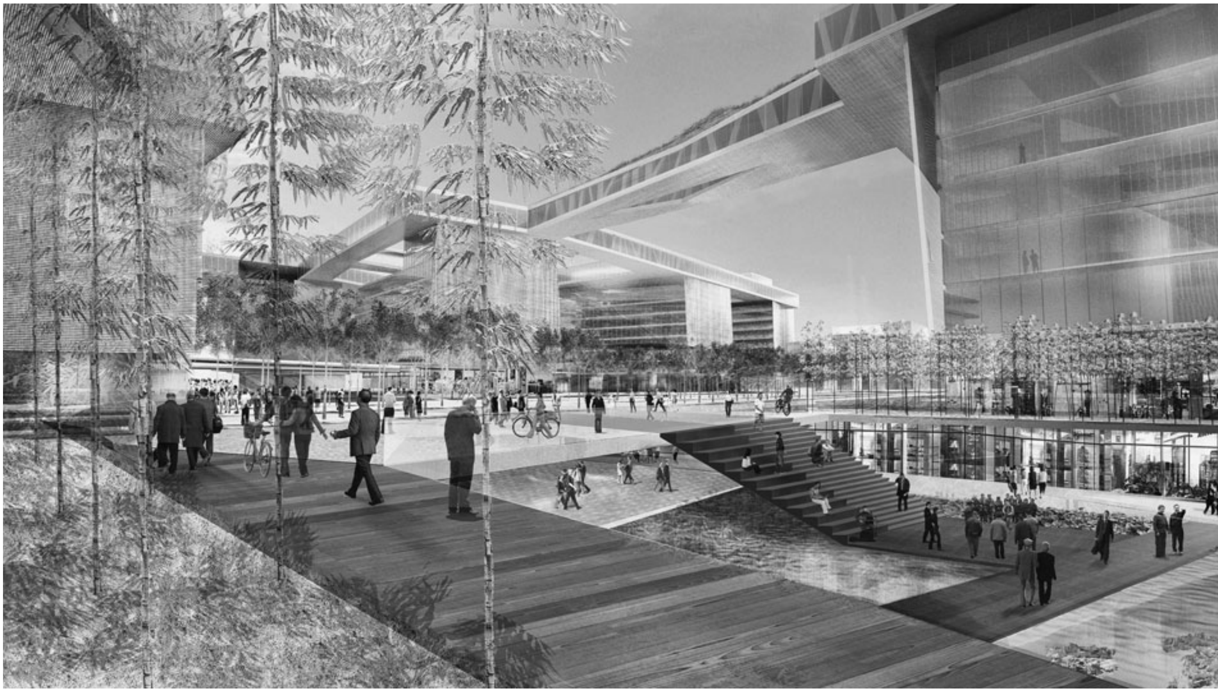
10.3 The sky level roof deck. The landscape surface shifts and slips to differentiate the programmatic areas and accommodate access to engage the lower levels. SPG Shanghai, SOM, Shanghai, China, 2010.

© SOM.

that bridges across the tops of all the buildings, conceptualized as the "sky" level. Two other horizontal planes of public or semipublic program were identified as "water" and "ground." The water level forms a physical and experiential connection to an existing river, which is below the ground or streetscape. Creating a three-dimensional urban realm by placing public space at three different levels in the project creates a risk that the density of people using the street plane could be diminished. "Rarely is this successful because often it robs street level or ground level of the energy of people moving there."[7] But the designers felt that the sheer density of this project would make the three-dimensional strategy work, and that in particular it was important to include the sky level, both as an open green space for the residents, and as a mechanism to facilitate some of the environmental strategies, in particular rain water capture and noise mitigation due to the nearby airport. The topography of the sky level is varied, and the landscape plane is sometimes folded vertically to form shade structures that create outdoor amenity spaces adjacent to the offices and hotels. Creating spaces for social activity was especially important.

Between the water level and the ground level, there is deliberately a great deal of vertical connection, both physical and visual.

> They're not simply stairways but they're also places for social connection, for people to sit and observe the urban theater of human action . . . Our thinking here was to create a place that was really very rich from the perspective of the pedestrian and then also to create this very rich porous environment both horizontally as well vertically.[8]



10.4 The ground level with views to the water level. There is significant vertical interaction between these two levels. SPG Shanghai, SOM, Shanghai, China, 2010.

© SOM.

The environmental systems included in the design proposal are very well developed for a competition project. Eric Long, Associate Director and structural engineer, notes that the competition process does not always include such detailed technical design, but that the SOM team here took a different approach:

> [In a competition] there's always a desire to very quickly come up with a compelling idea and to illustrate that very powerfully, and to not get very deeply into technical analysis because you don't know if you're going to win. You wouldn't do all that unless you thought you had a good chance to do it. But you can see in this competition we did here there's an enormous amount of technical analysis . . . Because we work together so hand in glove, the analysis we do is based upon experience and intuitive understanding about the way things work, so for us it's just a natural thing to involve structural as well mechanical engineering in these proposals.[9]

The team at SOM saw this technical development of proven systems as crucial to the design process. This is in part because China has instituted more stringent energy codes for new construction than the US, while simultaneously having very serious air pollution across most of its urban areas, but also Hartman argues, because it is part of the firm's mission:

> I should also say that in our interdisciplinary practice at SOM the other thing we take extremely seriously is high performance design and sustainability. We monitor all of our projects for energy consumption and water consumption. So across the firm we have a high-performance design portal that the project teams use to monitor the ongoing performance for our buildings from an energy and water point of view . . . [SPG Shanghai] is pretty significant. We achieved a 61 percent reduction in potable water . . . There's no smoke and mirrors hocus-pocus here. It's all based on current technologies.[10]

Various technologies are deployed to both ameliorate the environmental experience for users and mitigate the project's broader environmental impacts. The energy grid is optimized to reduce load, and photovoltaic solar panels supplement this. The green roof captures rainwater, and the proposal also employs bio-filtration using hydroponic greening veils[11] that stretch from the roof to the ground level, to filter gray water and improve air quality. These were designed in collaboration with a research team at Rensselaer Polytechnic Institute. Water from the veils and other surfaces are retained in the lagoons at the water level, which serve to retain and filter water, mitigating storm surge and minimizing strain on the sewage treatment system.

10.5 The bio-filtration veil: Hydroponic plants systems developed in collaboration with researchers at Rensselaer Polytechnic Institute to cleanse the air and the water. SPG Shanghai, SOM, Shanghai, China, 2010.

© SOM.

10.6 Three-dimensional exterior scrims on the façade balance daylight and solar gain. The patterns are tuned so that they can change as people walk or drive past. SPG Shanghai, SOM, Shanghai, China, 2010.

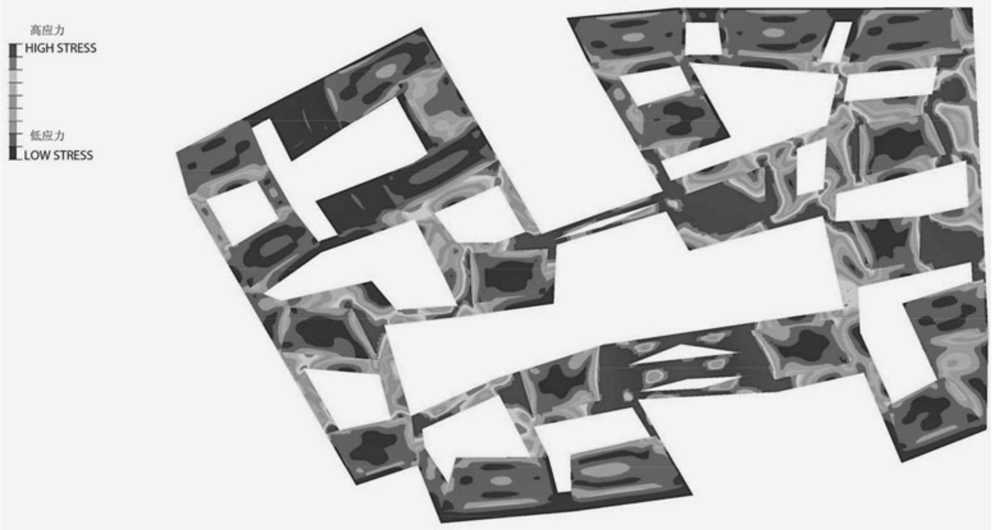
© SOM.

Additional sustainability measures include shading devices with a three-dimensional exterior scrim designed to minimize solar heat gain inside the buildings and tuned to create visual interest by projecting a different pattern on the surface as you walk or drive past. The buildings themselves and the roof level are positioned in such a way as to provide as much self-shading as possible. At the ground level bamboo plants are used for additional shading and to cleanse the air. Noise was also a concern, originating from the airport but also from the adjacent elevated roadway. The designers positioned the buildings so that there were no continuous tunnels or acoustic amplifying corridors, placing building façades non-parallel so that noise would be refracted rather than amplified. The rooftop greenery helps to absorb and minimize sound down at the ground level and there is also absorptive material on the underside of the roof where it's exposed public space to help to reduce noise. A tree bank around the perimeter and a soil berm also mitigate the noise.[12]

The structural planning for the project also considered environmental impact. The carbon inherent in structural materials (from the energy required for extraction of constituent materials, production, and transportation) is a significant source of CO_2 in the atmosphere. Concrete is the structural material of choice in China since steel is considerably more expensive.[13] To make cement, the active component of concrete, limestone and other ingredients must be heated to over 2000 °F, which requires burning fossil fuels. The production of one ton of cement causes approximately one ton of CO_2 making concrete production the third largest source of greenhouse gas pollution in the United States.[14] Thus eliminating concrete improves a project's sustainability. For the SPG development, the SOM team carefully studied the materials to be used in the project and from where they would be sourced and every effort was made to minimize the volume of material. The team came up with a patented design for structural slabs where concrete is replaced in the low-stress areas of the slab with lightweight materials like plastic bottles that were otherwise destined for landfill.[15] This strategy also has structural advantages as it reduces the weight of the structure (and in concrete buildings, the self-weight is usually the largest load that the structure carries). This reduction has the advantages of reducing stress, and thus further reducing the concrete required, and reducing overall mass is hugely important in seismic design. An earthquake is an applied acceleration, force is mass times acceleration, thus lighter buildings experience lower forces in seismic events.

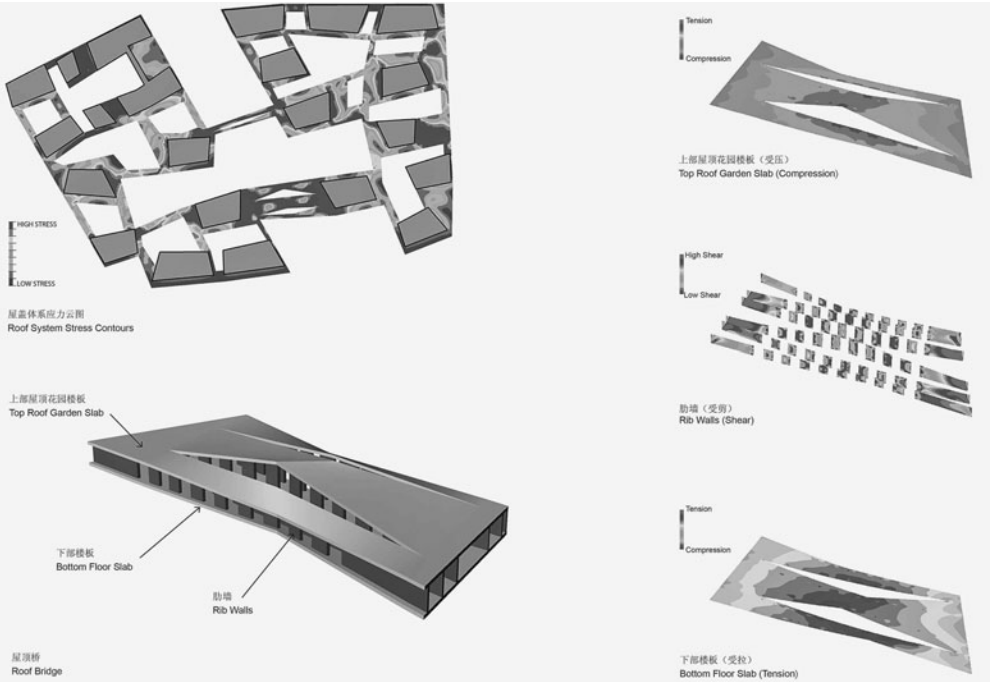
The series of buildings on the site are largely conventional concrete buildings with an outer perimeter of columns, an inner core and slabs (with the inserts described above being the only non-standard components). The roof deck, which covers each of the buildings and strategically spans between them, cantilevering past the edges to create the integrated sky level, is where the structural engineers were vital to the design process. The engineers created a model of the surface with loads and tested the resulting stresses. Long describes this process: "We looked at where stresses were high and where they were low to see if that presented an opportunity to inform the architectural design of the sky deck by looking at where demand was structurally."[16]

There was also a study of where best to locate the seismic isolation joints, to figure out if the roof should move as one piece in an earthquake, with the buildings swaying separately below,



10.7 Stress analysis for the roof deck sky level. The high stresses are where the deck acts as a bridge and highest are where the longest bridge over the street is required. SPG Shanghai, SOM, Shanghai, China, 2010.

© SOM.



10.8 Feasibility study for the structure of the roof deck sky level. Acting just like an I-beam the lower flange (the bottom slab) takes all the tension, the upper flange (the roof floor slab) takes all the compression and the shear forces are carried by the web (the rib walls). SPG Shanghai, SOM, Shanghai, China, 2010.

© SOM.

or if the roof should be broken up into several independently moving pieces.[17] As expected, the highest stresses are in the areas where the deck has the furthest to span, in particular where the deck spans over the street between the two halves of the project. For these sections a structural feasibility study was undertaken. The design that emerged from the careful analysis calls for a one-story-high bridge structure that acts like a giant I-beam. The top flange of the beam is the floor slab of the roof deck, the bottom flange is a continuation of the floor slab of the story below, and the web is made from a series of rib walls. The formal language of the bridges that was informed by the structural concerns was then carried around the entire sky deck connecting the buildings together.[18]

To address the issue of transit connectivity that the team had identified in the original governmental master plan, they proposed an electric rail shuttle system either at grade or one level above grade. This system would eliminate the need for a significant number of private car and taxi journeys from the new CBD to the intermodal transit system, and would provide enough stops such that all parts of the project would be no more than a five-minute walk away.[19]

The SPG Shanghai project brings together diverse expertise and creates a design that addresses urban connectivity and the human scale, energy efficiency, pollution mitigation and structural feasibility. Sarkisian thinks that the competition environment is one that can open

10.9 The structural language developed for the bridging portions of the roof deck continues around the whole sky level. SPG Shanghai, SOM, Shanghai, China, 2010.

© SOM.

up the design process particularly for engineers and that even when competition projects are not subsequently built, they result in innovation that can have long-term potential:

> I think that some of the best ideas from the engineering point of view come from competitions. Not all those ideas have been built yet, but there's a certain level of energy [in a competition] and a time where people are really looking for the new idea . . . If we look back at the last ten or so years some of the most important work that has led to other developments has actually come from competitions. So I think as Craig has mentioned, it's really a fluid process here [at SOM]. I think the obstruction [by engineers] that many architects feel perhaps exists, during the competition phase doesn't really exist. We try not to get in the way of the architects in terms of ideas. It's not about beams and columns; it's about these broader ideas of how we can advance.[20]

The team is clear that although the project was not ultimately built, the research and the technical and architectural development of solutions to the challenges of this site and program have already and will continue to influence their design work. The challenges of this project are essentially the challenges of the twenty-first-century city, particularly in developing nations. The solutions developed here were innovative and creative responses to these pressing issues, and were possible only through the thoughtful interdisciplinary process that the team undertook. Hartman asserts that the mutual understanding and common goals of the different disciplinary experts is the key to success:

> What really matters is . . . having the advantage of the intuitive understanding of the opportunities. The analysis is important in the end to verify that these things work, but an ability to sit together to know intuitively what the possibilities are and also to have a shared ethos about what we're trying to get to is really critical. If we didn't all share the same kind of aspirations regarding the city, regarding sustainability, regarding the things we talked about at the very beginning, I don't know if we'd ever get to the conclusion that we did on this project or the other things that we do. It's likely the conversation would not be nearly as productive.[21]

Notes

1 Mark P. Sarkisian, "Perspective," in *Designing Tall Buildings: Structure as Architecture*, New York: Routledge, 2012, p. 6.

2 Craig Hartman, Interview by authors, phone interview, San Francisco, CA, August 2, 2013.

3 Ben Mickus, Interview by authors, phone interview, San Francisco, CA, August 2, 2013.

4 Mark Sarkisian, Interview by authors, phone interview, San Francisco, CA, August 2, 2013.

5 Hartman, Interview.

6 Ibid.

7 Ibid.

8 Ibid.

9 Eric Long, Interview by authors, phone interview, San Francisco, CA, August 2, 2013.

10 Hartman, Interview.

11 These were designed in collaboration with a research team at Rensselaer Polytechnic Institute through the RPI-SOM partnership, CASE.

12 Mickus, Interview.

13 Sarkisian, Interview.

14 David Biello, "Cement from CO2: A Concrete Cure for Global Warming?," *Scientific American*, August 7, 2008, http://www.scientificamerican.com/article.cfm?id=cement-from-carbon-dioxide (accessed August 18, 2013).

15 Sarkisian, Interview.

16 Long, Interview.

17 Ibid.

16 Hartman, Interview.

19 Mickus, Interview.

20 Sarkisian, Interview.

21 Hartmann, Interview.

– 11 –

Keelung Harbor Project

Design Architects	Neil M. Denari Architects, Inc.
Façades and Structure	Thornton Tomasetti, Los Angeles
Logistics	ARUP, Hong Kong
Local Façade Consultant	Meinhardt, Hong Kong
Local Architect	Fei & Cheng Associates, Taipei, Taiwan

The design of the Keelung Harbor Project involved a broad collaboration among a variety of partners, but the majority of this discussion will focus on the association between NMDA, Inc. and Thornton Tomasetti, beginning with the background of the firms.

Neil M. Denari Architects, Inc. (NMDA)

Neil Denari, educated at the University of Houston and Harvard Graduate School of Design, worked for Polshek Partnership (now Ennead Architects) before starting his own firm in 1988. Denari's international reputation was established early in his career: in 1986, at age 29 he was honored as the youngest architect in New York Architecture League's *40 under 40*. That same year, the Cooper Hewitt Museum acquired Denari's work for the permanent collection. Six other museums have followed suit including the Museum of Modern Art in New York and the FRAC Center in Orleans, France. His detail drawings, simultaneously technical and experiential, are widely known in the field for fostering an entirely new approach to drawing in the digital age. As both an architect and educator who teaches at UCLA and other renowned universities, Denari inspires students around the world through both practice and discourse. Numerous institutions have recognized Denari's contributions and he has won some of the highest honors in architecture including an Academy Award from the American Academy of Arts and Letters and a Los Angeles AIA Gold Medal.

NMDA is a boutique-size architectural practice working at a range of scales in a highly crafted, super clean, yet firmly contemporary aesthetic. Preston Scott Cohen, designer, author, and Chair of Architecture at the Harvard Graduate School of Design, states that Denari's work "is widely regarded to be the most refined and experimental in the genre of machinist modernism, to which he has undoubtedly added to the repertoire. Simply put, his work decidedly represents a concrete and theoretical contribution to the discipline."[1] Built projects have included a number of banks throughout Japan for the Mitsubishi Trust Financial Group, and HL23, a 14-story residential tower completed along the High Line in New York City that received awards from the AIA in both New York and Los Angeles. Despite the growth in number and scale of projects, the firm has developed a very focused, detail-oriented body of work that is deeply attuned to design.

Thornton Tomasetti (TT)

Thornton Tomasetti, founded in 1956 as a structural engineering consultant practice, now provides services through six integrated working groups: Building Structure, Building Skin, Building Performance, Construction Support Services, Property Loss Consulting and Building Sustainability. The firm employs over 700 engineers, architects and professionals in 28 offices throughout the world. Although projects range in scale, the firm has developed an industry-wide reputation for mega-scale engineering with the structural design for some of the tallest buildings in the world today, including the Cesar Pelli-designed Petronas Towers in Kuala Lumpur, the Shanghai Tower designed by Gensler, and the 1,000 meter high Kingdom Tower in Saudi Arabia designed by Adrian Smith + Gordon Gill Architecture.

Thornton Tomasetti is collectively owned by its employees and despite the firm's size, the working methods, at least in the Los Angeles office, demonstrate an intimate approach to consultancy. Bruce Gibbons, TT's Managing Principal and a member of the Board of Directors, leads the firm in the western US and also heads the Building Structure group in the Los Angeles office. For the Keelung Harbor project, Gibbons worked with Ben John, Senior Project Engineer and with TT's Building Skin practice, led by architect Mark Dannettel, a Principal in the firm, who teamed with Brian Guerrero, an Associate and façade consultant. Gibbons and Dannettel have each practiced for over 25 years, bringing to the following case study a plethora of experiences from a wide range of projects all over the world.

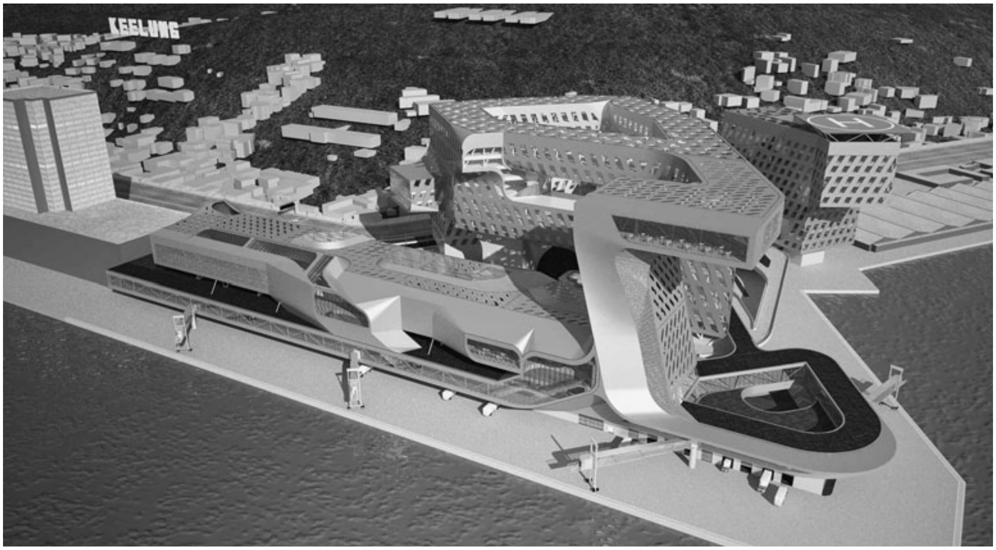
Keelung Harbor Project Introduction

The port of Keelung, situated a short drive north of Taipei, is one of Taiwan's largest ports, docking both cargo and cruise ships, sometimes with as many as 10,000 passengers per day. In 2012, the Keelung Harbor Port Authority held a two-stage competition calling for a new complex of buildings on a five-hectare site. The competition sponsors called for teams to

"Develop the design for a modern passenger and cargo terminal, transfer station and maritime gateway art plaza that will improve the quality of passenger and cargo services provided by the harbor, accelerate development in the surrounding areas and promote local prosperity."[2] Proposals were submitted from 31 firms from around the world. The jury, which included two Americans and five Taiwanese, selected five teams to develop proposals further. The shortlist included Neil M. Denari Architects, Inc. (US); Platform for Architecture+Research (US) and Series et Series (France); QUEBEC INC/Alain Allard (Canada); Mecanoo Architecten (The Netherlands); and Asymptote Architecture (US). The team, composed of NMDA, Thornton Tomasetti's Los Angeles Structure and Skin practices and logistics experts from Arup Hong Kong, won the competition in late September 2012 and a contract was signed in early October.

Aaron Betsky, one of the distinguished jurors for the competition, describes the selection process: "We kept being tempted by the beauty of Asymptote's curves, but then kept coming back to the difficult rightness of the Denari design . . . It demonstrates the power of architecture—and architecture competitions—to do just that: find a form that intensifies, condenses, and catalyzes a context into something it can be."[3] Michael Speaks, the other American on the jury, agrees with Betsky: "It was a difficult decision, but the Denari entry provided the best fit for the design challenge posed by the site and other constraints, including a complex phasing and building process. But it also gives us an entirely fresh approach to the 'icon' by deftly but powerfully addressing the challenge to design a signature building that responds to local constraints and global opportunity."[4]

The winning scheme is a stretched, molded bar that rises as a tower to form an iconic gateway to the harbor. The cladding adds to the graphic image, composed of a lightweight skin



11.1 Aerial rendering of the Keelung Harbor Project. NMDA, Thornton Tomasetti, Keelung Harbor Project, Keelung City, Taiwan, 2017.

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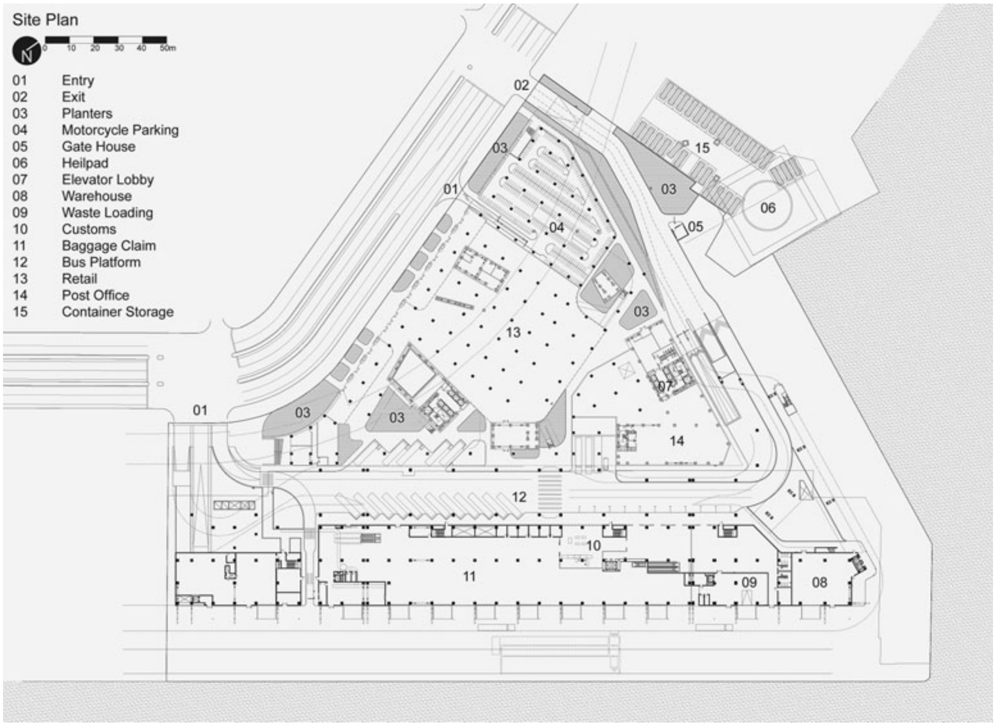


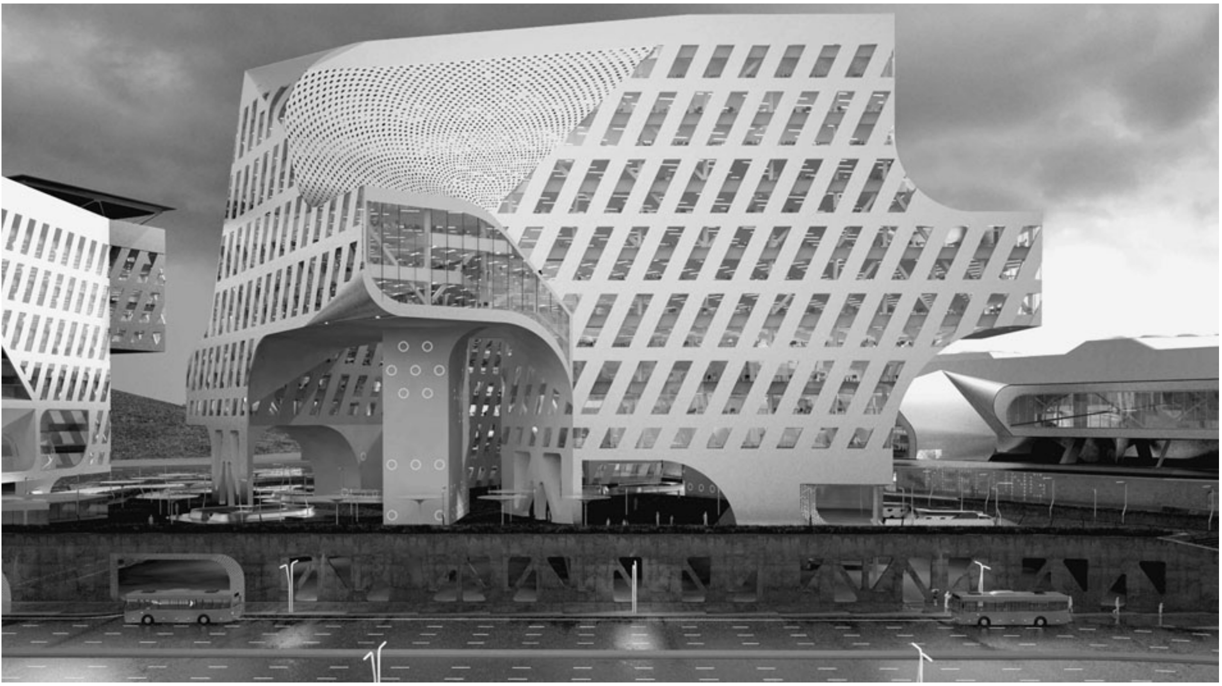
11.2 Site plan. NMDA, Thornton Tomasetti, Keelung Harbor Project, Keelung City, Taiwan, 2017.

© NMDA.

of painted aluminum with slanted windows that mimic the rainy climate. Chartreuse and sea foam green accent colors abstractly integrate the building into the surrounding verdant landscape. There are two main programmatic enclosures: the terminal and office buildings. The three-story terminal building fills the 55 meter wide site, and includes passenger lobbies, boarding/arrival gates, shopping areas, restaurant and a boardwalk called “the shoelace” that engages the surrounding urban fabric and connects the various programs. The office building, on the other hand, accommodates a vastly different program. The 14-story building, based on a courtyard typology, is a light-filled tower at the northern corner of the site. The tower anchors a cantilevered restaurant that floats above the landscape, offering dramatic views of the surrounding context.

After the competition win, the most significant changes in the design resulted from shifts in the project scope, including program content and square footage. In the end, these adjustments permitted a simpler plan and experience for the terminal (and better aligned project costs with the budget) than the original competition entry. The required area in the office building decreased, so the building height was lowered eight meters from the winning scheme. The terminal was also modified, becoming a simpler building as a result of the reduced program.

The changes in the scope of work prompted an adjustment to the bid schedule: the terminal and office buildings were separated into two different bid packages with the terminal



11.3 Exterior rendering showing the painted aluminum and canted windows. NMDA, Thornton Tomasetti, Keelung Harbor Project, Keelung City, Taiwan, 2017.

© NMDA.

slated first for construction. The NMDA–TT team developed the project for the Preliminary Design package (which is equivalent to Schematic Design in the United States) for submission in April 2013. From that point, NMDA paired with executive architects Fei Cheng in Taiwan and Meinhardt in Shanghai to develop the bid documents in time for the September 2013 deadline. With these in hand, construction of the first phase could commence in early 2014.

Design Team and Structural Strategy

The initial proposal for Stage One of the competition was designed by NMDA, but after selection for the shortlist, Denari enlisted a team to develop the project for Stage Two of the competition. Denari solicited the help of longtime friends and colleagues at TT, Bruce Gibbons and Mark Dannettel, who brought on team members Ben John and Brian Guerrero. Since TT Los Angeles is located a couple of miles from the NMDA office, the proximity facilitated weekly in-person meetings with the whole design team, enabling a highly integrated and collaborative working process. Guerrero remarks that, “the ability to collaborate in a workshop fashion—being physically together in a room—can define the success of a project.”[5]

Throughout the initial design and development process, the architecture-engineering team worked closely to assure coherence in the aesthetics and efficiency of the systems.

This working method proved crucial for the Keelung Harbor Project since the structural and façade systems fundamentally impact one another and play a prominent role in the architectural expression. Denari describes the importance of communicating in a way that enables engineers to bring concordant ideas to the table that "relate to our aspirations," saying, "I always enjoy the interaction with the structural engineers because I think it's at the heart of making a project great rather than simply disciplining it or reverse engineering something."[6] Gibbons corroborates the supportive nature of their working relationship, saying that "[Neil] has a very strong aesthetic . . . We worked to maintain the premise of what he was doing . . . and get everything lined up in a sensible way structurally."[7] Denari explains that structure always plays a part in the conceptual development and "architectural rhetoric," such that he and the NMDA team usually come to the table with ideas to start the conversation with the engineers. In the case of Keelung, even though engineers were not initially involved in the Stage One competition entry, Denari describes the importance of designing the structure with engineers early in schematic design. John reflects on this process, saying, "One of the great things about working with Neil is that it's an iterative process that's really collaborative."[8]

11.4 View of the HL23 residential tower from the High Line in New York City. NMDA, Thornton Tomasetti, Keelung Harbor Project, Keelung City, Taiwan, 2017.

© NMDA.

This cooperative mode of structural design is not always the approach taken by architects; strategies vary widely across the discipline. Denari notes that at one extreme, architects such as Frank Gehry design sculptural forms and the structure must conform (even if it means the resulting system lacks efficiency); the opposite approach is taken by architects such as Richard Meier, who employ rational grid systems to guide design development. Denari doesn't fit into either camp, saying, "I don't have any particular formulaic philosophy . . . Projects have a life of their own, and if anything, most of our work tends to be a hybrid between a lot of surface and exposed vector structure, maybe because I'm interested in both/and versus either/or."[9] In the case of NMDA's HL23 residential tower in New York City, for example, cross bracing is set back from the floor edge, but an applied frit pattern on the windows announces the structure to the outside, creating a perception of structure that isn't exactly there.

Contradictions play out in HL23 in numerous ways, creating illusion and adding interest. The building is at once graphic and object-like; grounded and hovering; tall and slim from one viewpoint, but stout from another. Similar sorts of contradictions play out in the Keelung project, which is both flat and deep, grounded but also floating, heavy and light; the structure is sometimes expressed and sometimes hidden. These visual effects and experiences are made possible through a highly refined attention to detail and coordination of the building systems amongst the architecture engineering team.

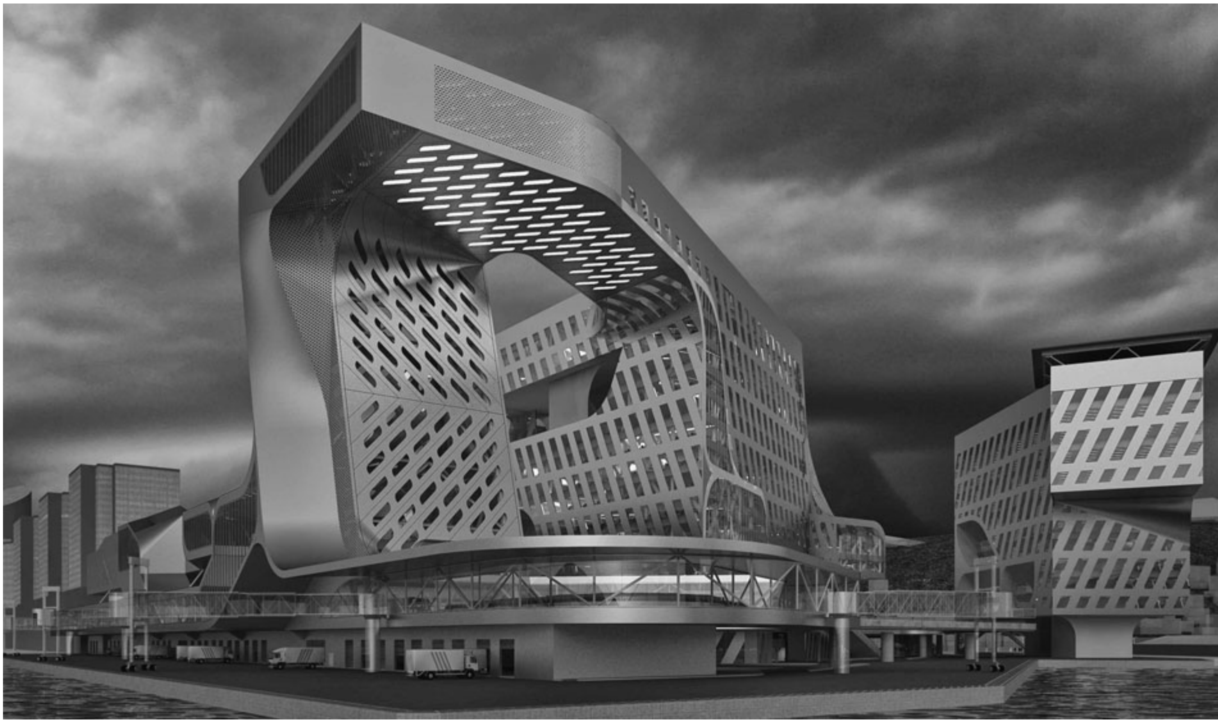
11.5 Interior view of HL23 showing the frit pattern on the glazing. NMDA, Thornton Tomasetti, Keelung Harbor Project, Keelung City, Taiwan, 2017.

© NMDA.

Office Building Design Development

The office building, the more complex of the two structures, is scheduled for construction in the second phase. The 53,000 square meter (570,000 square feet), 64 meter (210 ft) tall building contains the Harbor authority, police station, post office transfer facilities, a weather station, and numerous harbor administrative offices. The tower, a bent bar with a folded arch shape, shifts in response to the site boundaries, views and climate.

Since the required floor area changed a number of times during preliminary design, TT Structure created a Grasshopper definition[10] to more efficiently locate the structural members. Grasshopper is a visual scripting software that plugs into Rhinoceros (both by McNeel), a precise, 3D modeling program with robust capabilities. Rhino happens to be NMDA's software of choice, so when they altered the surface forms, these new geometries were easily fed into TT's Grasshopper definition. As a result, structural updates could happen relatively quickly and thereby feed back into the architectural model. An example of how compatible software programs can facilitate the design development is shown by the intersecting planes and folds in the architectural model, which created challenges for locating the structural supports.[11] The team worked to hide grid shifts and coordinated with NMDA when the bracing could be



11.6 The office building will serve as a "gateway" to the harbor. NMDA, Thornton Tomasetti, Keelung Harbor Project, Keelung City, Taiwan, 2017.

© NMDA.

exposed. Ideally, from an engineer's standpoint, columns are vertical, because when they're angled they carry an extra horizontal load and those forces must be accounted for in the structural design. Gibbons describes, "If we needed to change the direction of a column, we did it in the floor level where we have a mechanism for dealing with that out-of-balance force. So we spent a lot of time back and forth with Neil's office with iterations on geometry, and we used Grasshopper to . . . locate the structural members . . . and we looked at optimizing the location of these."[12] By putting the "kink" in the column at the floor, the consequential horizontal force can be carried away by the floor plate. If this happened at mid-story the column would have to be bigger to resist the inevitable bending that would occur.

Gibbons explains that in the past, spreadsheets were the dominant form of output for structural engineers, but in recent years Grasshopper has added efficiency to the process: the software facilitates quick adjustments and integration with the architecture, but can still output spreadsheets when needed. Gibbons' colleague Ben John created the Grasshopper definition, saying it became a critical part of visualizing ideas and furthering the design from both architectural and structural perspectives. "Even from the very early stage of the project we ran Grasshopper routines that could help us to know what the structure would look like within the building; we created routines that analyzed [NMDA's] surfaces and placed structure within them."[13] The Rhino-Grasshopper model was also used to develop analytical models and formed the base geometry for a Revit model, which TT used to generate their Preliminary Design drawing package.

Adding to challenges of designing structure for the sculptural forms of the Keelung project, the site is noted for seismic activity which necessitates hefty bracing, and this became part of an architectural aesthetic that emphasizes diagonal vectors throughout the project. Gibbons describes the office building as,

> highly sculptural . . . with some long spans and substantial cantilevers. There aren't many places where the building comes to the ground and it's in a high seismic zone so the challenge was providing a robust lateral system in limited locations. In order to get some of the long cantilevers to work we needed to put in perimeter trusses, and it's generally not a good idea to mix moment frames with bracing because that can focus seismic energy into the soft moment-framed stories. So we also used braced frames for the lateral system which are more compatible with the gravity trusses, and this reinforces the bracing theme throughout. The office floors also have long spans across the building and in order to maintain the shallow story height, we've notched the floor beams at their ends to allow ductwork through without giving up too much story height.[14]

The façade design resulted from a close collaboration among TT Skin, TT Structure and NMDA. Mark Dannettel, the regional leader for TT's Building Skin practice, had worked informally with Denari in the past, providing construction input for the HL23 project, in his previous position as a design-build contractor. He describes TT Skin's scope of work for the

Keelung project: “Typically a façade consultant is a technical consultancy . . . We are basically responsible for guiding the architect to select appropriate systems or technologies for different portions of the façade and . . . in this case we did all the façade detailing for the completion of the DD package, which is typically the cut-off point for the US-based design architect for doing work in Asia.”[15] Dannettel’s colleague Guerrero describes that from the perspective of the façade design, 75 percent of resources were spent on the office building and 25 percent on the terminal building.

The molded curvilinear surface and canted geometry added to the complexity of developing the façade systems. Given the very large area of skin surface as well as the repeating geometry and fast-track construction schedule, the team opted for a prefabricated, unitized curtain wall system. NMDA used metal cladding with great success on the HL23 project and TT Skin brought expertise on unitized systems manufactured for Asian markets. Guerrero, who worked at Front while consulting on HL23, describes that on a project the scale of Keelung, unitized systems can be very efficient for manufacturing and installation. The unitized curtain wall system provides other benefits as well: “[It] is a pressure-equalized system and also works better with building movement, wind loads and racking,”[16] and contributes significantly to the building’s overall energy performance.

The diagonal apertures added challenges to the design of the unitized system, but were not unresolvable. Dannettel explains the development of the system:

> The only thing that is a little bit tricky is that it’s diagonal instead of vertical and that causes some problems for the self-weight: it wants to rotate around on its own dead weight so we had to do some extra engineering to make that work. We made adjustments with Neil early on about maximum angle slope and width of panels . . . striving for constructability.[17]

Aluminum is extruded into the specific shape then the whole system, including gaskets and glazing, is assembled in the factory and transported to the site. Practicality drove decisions about the width of the unitized modules, 5′–0″ wide between the jambs, which optimizes the glass and framing for manufacturing.

Although the majority of the façade system utilizes a curtain wall systemization, the skin pulls away from the floor plate about mid-height on the office building, creating an interstitial indoor–outdoor space. Guerrero notes that throughout the design, but also in the case of this special condition, “[Neil] wants to do something with geometry and create dynamic space but at the same time he’s very pragmatic in the system selection.”[18] The screen design required close coordination with the structural engineers to develop the support system. “One of the advantages of having TT structure involved was that they are right down the hall . . . we could interact with them on a regular basis and talk about movement and trying to limit deflections and prioritize during the process of developing the systems. These were advantages of working side-by-side.”[19] Their resolution involves a 1.8 meter wide catwalk that supports the screen system and enables access for maintenance.

Terminal Building Design Development

The terminal, the simpler of the two buildings in terms of program, structure and skin, is an "articulated loft building"[20] of 28,000 square meters (310,000 square feet). With thousands of cruise passengers moving through the doors each day, an unobstructed floor plan allows for open, fluid circulation and easy navigation. The expansive space required long spans at the roof, which is lightweight, but made even more so because of the vast ETFE (ethylene tetrafluoroethylene) skylight that washes the space with daylight.

Gibbons explains that the team located structure in the terminal building through close collaboration with the architecture: "In this one, the real challenge (because of the open nature of the terminal) was how to locate vertical bracing and that was an iterative process. We went back and forth with Neil's team over several iterations before we merged on the final solution."[21] TT Structure dealt with the design's huge cantilevers by creating trussed tubes with bracing in the walls, floor and ceiling. "The nice thing is that Neil understood the demand for this and also how to integrate these as design features so that sometimes [the bracing is] exposed and becomes part of the architecture."[22]

The façade design of the terminal building employs fewer diagonals and more standard, less complex geometry than the office building. Still, the materiality remains consistent and a

11.7 Interior rendering of the terminal building with expansive skylights and open circulation. NMDA, Thornton Tomasetti, Keelung Harbor Project, Keelung City, Taiwan, 2017.

© NMDA.

unitized aluminum curtain wall stretches taut across the surface. In both the terminal and office buildings, Guerrero explains that they "used [the] same extrusion dies[23] for the verticals. Neil wanted to optimize the depth of the overall system to add to the efficiency of the façade."[24] The prefabricated system provides numerous environmental benefits. "Given the attributes of the unitized curtain wall, with insulating laminated glass with low-e coatings, these brought the façade performance on par to be sustainable and responsible in terms of energy efficiency."[25] The designers also eliminated thermal bridging through an insulative layer within the units and mitigated cold bridging by utilizing a thermally broken aluminum edge adapter. In the end, all the curtain wall details for the terminal building became a part of the architectural drawing set for the Preliminary Design package.

Construction Documentation and Local Partnerships

LARGE-SCALE projects such as the Keelung Harbor buildings require sophisticated coordination of design, systems, constructability and code compliance. Design architects and engineers throughout the world find that local partnerships lead to better integration of codes for permitting, a complicated and sometimes lengthy process. As it has already been noted, Denari has a strong sense of construction and works closely with the executive architects throughout the process. For this project, the arrangement with local architects, Fei & Cheng Associates (FCA), is technically 50–50: FCA contractually has more responsibility regarding the detailing, but NMDA is hugely invested in the design, working closely with the local architects and will continue to do so throughout construction.

Denari noted that NMDA has "a friendly, good relationship [with FCA]. Michael Fei completely understands how we work in the US since he was trained and worked on the East Coast."[26] Philip Fei and Mei Cheng established FCA in 1974 after studying in both Taiwan and the US. The practice has completed numerous projects as design architects and they've also acted as the executive architects for a range of competition-winning proposals that are currently under development, including RUR Architecture's Kaohsiung Port Terminal and Cruise Service Center and Taipei Pop Music Center, as well as Sou Fujimoto's 21st Century Oasis in Taichung.

NMDA communicates with FCA using both traditional and contemporary means, bolstered by Denari's belief in the power of drawings and renderings to convey the intent of the design. "We give them a lot of . . . drawings that are not dimensioned all the way through, so it's collaborative in that sense. We are also using renderings as a tool to communicate our intent so the renderings continue to get built up with detail."[27] Although this mode is not necessarily a standard form of communication between design and executive architects, it points to Denari's strong sense of the aesthetic project. The digital model also proved helpful in communicating with a range of partners: the local engineers, the structural engineer of record and the façade consultants in Shanghai. NMDA also helps to coordinate the local consultants, since TT shifted detailing responsibility to the local firms after submission of the Preliminary Design package.

11.8 The Keelung Harbour buildings are scheduled to be completed in 2017. NMDA, Thornton Tomasetti, Keelung Harbor Project, Keelung City, Taiwan, 2017.

© NMDA/Nephew.

The collaborating team was prepared to send out the terminal building bid package at the end of September 2013, just one year after the competition win, and the two-phased construction process is scheduled for completion in 2017. The Keelung Harbor Project will be the largest completed built work for NMDA. Despite the huge scale and scope of the project, the design by the interdisciplinary team demonstrates the power of invention to realize complex forms and effects on a finite budget.

Notes

1 Neil Denari and Preston Scott Cohen, "Discussions in Architecture: Neil Denari and Preston Scott Cohen," Lecture and Discussion, Harvard GSD, Boston, September 4, 2010.

2 https://www.competitionline.com/en/competitions/141029/true (accessed March 18, 2014).

3 Aaron Betsky, "Neil Denari Wins Keelung Harbor Building Competition," Architect Magazine: Architects, http://www.architectmagazine.com/architecture/neil-denari-wins-keelung-harbor-building-competition.aspx, September 17, 2012 (accessed March 18, 2014).

4 Michael Speaks, Comments to Aaron Betsky, "Neil Denari Wins Keelung Harbor Building Competition," Architect Magazine: Architects. http://www.architectmagazine.com/architecture/neil-denari-wins-keelung-harbor-building-competition.aspx, September 17, 2012 (accessed March 18, 2014).

5 Brian Guerrero, Interview by authors, phone interview, Los Angeles, CA, July 9, 2013.

6 Neil Denari, Interview by authors, phone interview, Los Angeles, CA, June 25, 2013.

7 Bruce Gibbons, Interview by authors, phone interview, Los Angeles, CA, July 8, 2013.

8 Ben John, Interview by authors, phone interview, Los Angeles, CA, July 26, 2013.

9 Neil Denari, Interview by authors, phone interview, Los Angeles, CA, June 25, 2013. Denari is referencing Robert Venturi's seminal text, *Complexity and Contradiction in Architecture*, first published in 1966, which defined the Postmodern movement in architecture. Venturi rejects Modernism for its "forced simplicity" and proposes a more complex and meaningful design aesthetic that engages the public through conditions that are "both-and" rather than "either-or."

10 A Grasshopper definition is the term used to describe the visual script that creates some form of output (e.g. geometry or numbers).

11 Gibbons, Interview.

12 Ibid.

13 John, Interview.

14 Gibbons, Interview.

15 Mark Dannettel, Interview by authors, phone interview, Los Angeles, CA, July 5, 2013.

16 Guerrero, Interview.

17 Dannettel, Interview.

18 Guerrero, Interview.

19 Ibid.

20 Denari, Interview.

21 Gibbons, Interview.

22 Ibid.

23 Extrusion dies are the shape molds for the aluminum.

24 Guerrero, Interview.

25 Ibid.

26 Denari, Interview.

27 Ibid.

– 12 –

Port House

Architect	Zaha Hadid Architects (London, UK)
Local Architect	Bureau Bouwtechniek (Antwerp, Belgium)
Stability	Studieburo Mouton (Ghent, Belgium)
Restoration	Origin (Brussels, Belgium)
Services	Ingenium (Bruges, Belgium)
Acoustics	Daidalos Peutz (Leuven, Belgium)
Contractors	Interbuild (General), Victor Buyck Steel Construction, Groven + NV (façades construction)

ALTHOUGH multiple experts collaborated on the design of the Port House in Antwerp, the case study focuses on the roles of Zaha Hadid Architects, Studieburo Mouton and Bureau Bouwtechniek, beginning with the background of the design firms.

Design Architect: Zaha Hadid Architects

ZAHA Hadid Architects is one of the most prominent, widely influential and recognizable contemporary design firms in the world. The office, based in London, is led by Baghdad-born Zaha Hadid, who graduated from the Architectural Association in London in 1972. Three decades later in 2004, Hadid became the first woman to win the Pritzker Prize, the highest prize in architecture, awarded once each year. The Pritzker Prize Jury Citation states, “Clients, journalists, fellow professionals are mesmerized by her dynamic forms and strategies for achieving a truly distinctive approach to architecture and its settings. Each new project is more audacious than the last and the sources of her originality seem endless.” As her work reached laudable heights, her firm has grown to employ almost 400 people. The work, ranging from furniture to prominent cultural buildings, demonstrates continual experimentation with materials and technologies to realize new forms and effects.

The firm maintains an impressive reputation for innovation. Recent works include the Guangzhou Opera House, a fluid, artfully urban 70,000 square meter cultural center located in the new Zhujiang district of Guangzhou, China; and the London Aquatics Center, completed for the Olympic Games. Zaha Hadid Architects has won numerous architectural competitions throughout the world, successfully constructing numerous highly acclaimed, large-scale projects. The Port House project in Antwerp is another competition winner and serves as the subject of the following case study.

Structural Engineers: Studieburo Mouton

Based in Ghent, Belgium, Guy Mouton positions Studieburo Mouton as a design-oriented engineering firm with a solid reputation for collaborating with architects early in the design process to achieve aesthetic goals as well as efficiency standards in structural and stability design. The firm is a small practice of both engineers and architects working on projects throughout the Flemish region. Trained first as an architect and then as an engineer, Mouton describes himself as an "engineer architect" with an intimate understanding of the architect's approach. "It is important to harmonize the structure and architecture into a unified concept,"[1] says Mouton. Several past projects exemplify this approach to design, including the Sport Center of Boerekreek with Coussée & Goris Architecten and the Cultural Centre De Grote Post in Ostend with B-architecten. Current projects include Cultural Centre De Waalse Krook in Ghent with RCR Aranda Pigem Vilalta and Coussée & Goris; Nature Reserve Het Zwin in Knokke-heist with Coussée & Goris and Gafpa; and the Erasmus School in Brussels with Bevk-Perovic arhiktekti and B-architecten.

Studieburo Mouton's work was featured in an exhibition at Witte Zaal in Ghent titled *Designing Together*. In the catalogue, Mouton writes about the need for collaboration from the very start of a project:

> Conducting a stability study for a design goes much further than simply calculating a given situation. The office is ready to be involved in the architect's very earliest design stage. It is the intense cooperation between the architect and the engineer in which architecture and structure both reinforce and challenge one another: this is designing together.[2]

This was the approach taken by Mouton in the Port House design with Zaha Hadid Architects in this case study.

Local architects: Bureau Bouwtechniek (BB)

Bureau Bouwtechniek (BB) is a well-established research and consulting firm specializing in building technique. BB was founded in 1995 by Professor Architect Jan Moens and currently employs more than 50 architects and engineers who work closely with the designing architects to provide technical support while maintaining a pioneering spirit. Annually, Bureau Bouwtechniek supports an average of about 280 projects ranging from technical renovation advice and assessments to in-depth guidance on energy and constructability. BB has completed projects throughout Belgium, often in international collaborations. Their portfolio includes the Museum aan de Stroom (MAS) in Antwerp (2000) with Neutelings Riedijk, the City Hall in Montigny-Le-Tilleul with V+, the Queen Elisabeth Hall in Antwerp with Ian Simpson Architects, and the Royal Museum for Fine Arts in Antwerp with Claus and Kaan Architecten.

Port House Case Study, Antwerp, Belgium, Design Build Contract

In 2008, the Port Authority of Antwerp held an open call competition to design new office spaces for administrative and technical employees and to envision a building that would act as a gateway to the second largest port in Europe. Located at quay 63 at the site of an existing historic Fire Station, the port area, known as Het Eilandje, is part of a massive redevelopment

12.1 A rendering of the new administration building for the Port Authority. Zaha Hadid Architects, Studieburo Mouton, Port House, Antwerp, Belgium, 2015.

Courtesy of Zaha Hadid Architects.

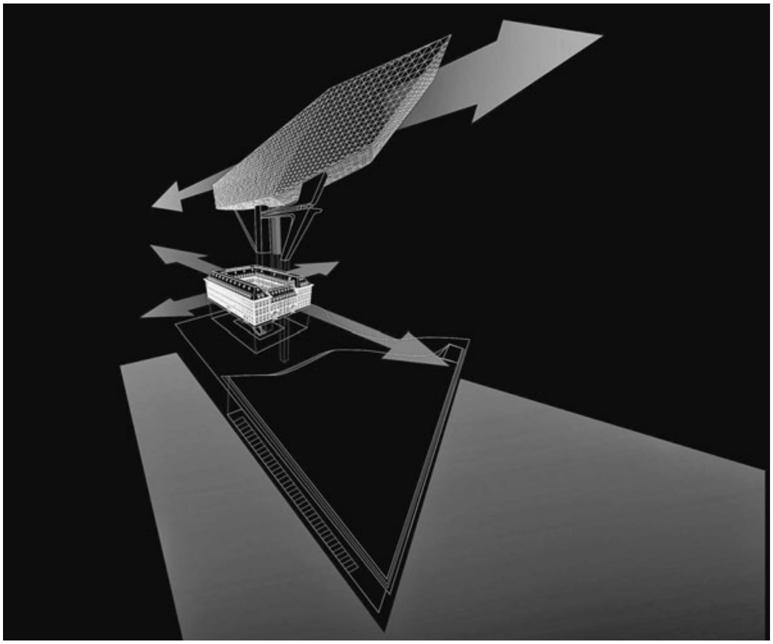
effort. Nearly 100 firms entered the competition and the team led by Zaha Hadid Architects was one of five finalists selected. The jurors ultimately chose the proposal because it "preserves as much as possible of the dignity of the present building as a monument, adding a new object to the site" and because of Zaha Hadid Architect's reputation and proven ability to design and construct projects of outstanding quality.

The Team

When questioned about the trajectory of ideas in her work, Hadid has said that,

> The idea of flotation lead to research in structure, and therefore, our work with engineers and structures is really important, not because we need them to figure out how to make the building stand up, but to interpret how these [ideas can] happen.[3]

A floating bar above the existing Fire House was the original design idea for the Port House, and this concept was further developed by the project team.



12.2 The new Port House addition hovers above the existing fire house. Zaha Hadid Architects, Studieburo Mouton, Port House, Antwerp, Belgium, 2015.

Courtesy of Zaha Hadid Architects.

From the beginning of the competition, Zaha Hadid led the design process with director Patrick Schumacher, and associate Joris Pauwels, working as Project Architect. ZHA teamed with engineers and an executive architecture firm, Bureau Bouwtechniek, that was enlisted for their local expertise and ability to provide on-site management in the Dutch language. The team that won the competition continued to work together throughout the design and construction process, meeting regularly in person and daily on the phone.

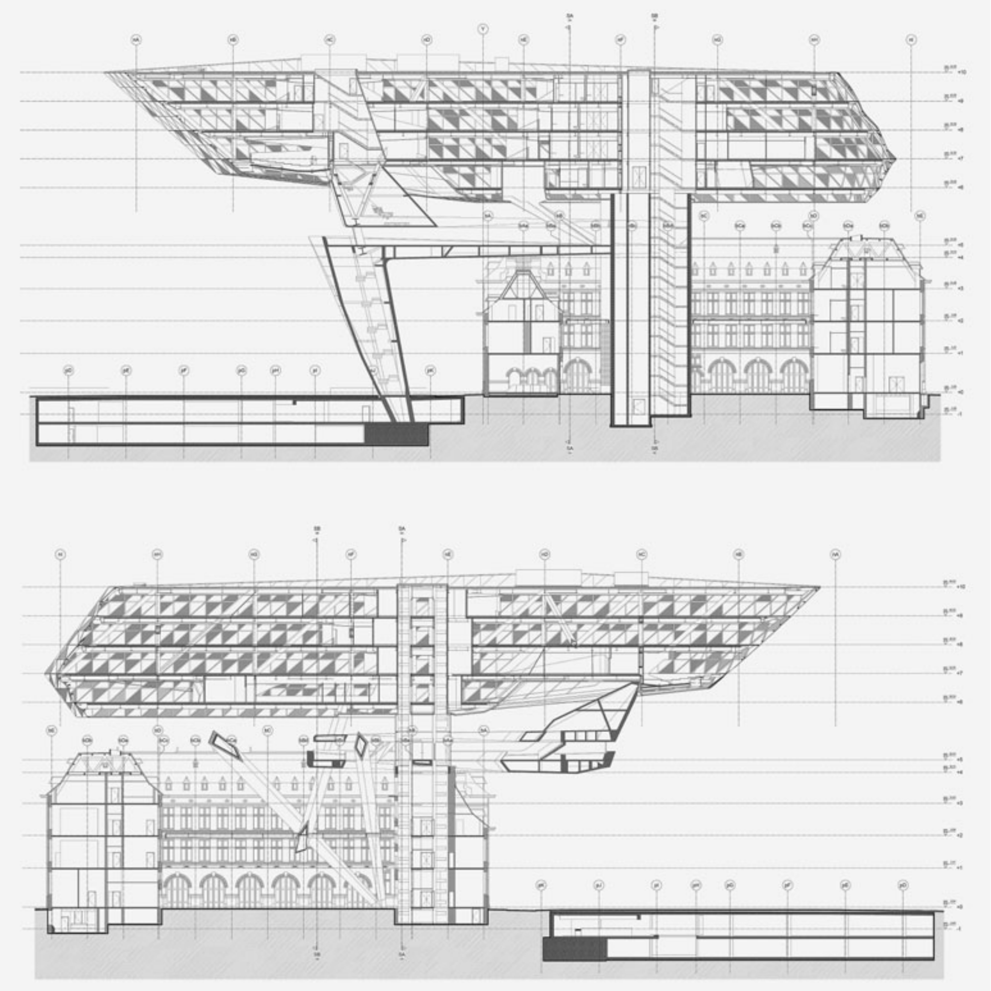
Pauwels describes the team that worked together from the very first concept meetings:

> Obviously, putting together the right team for a project is crucial for a successful delivery. Trust is an important factor of any collaboration and mutual respect for the specialists you choose to assist in various fields is essential. Rather than dictating this or that aesthetic, we try to develop ideal scenarios that make sense across disciplines . . . Although it is the first time we worked with them, Bureau Bouwtechniek definitely lives up to their credentials and form an important part of the team in advising us technically in relation to local building customs and regulations, dealing with local authorities, etc. They are also our cost consultants and in charge of the day to day site supervision . . . For the structural design we chose to work with Studieburo Mouton, which is run by a former professor of mine at St Lucas in Brussels. Knowing each other is comfortable in the sense that there is already that basis of trust from the start. It speeds up the decision making process and is a bonus when needing to resolve stressful situations that inevitably occur during a lengthy design and construction period.[4]

Evolution of the Design: Form and Structure

THE 49.9 million Euro building, which includes 2.1 million Euros for restoration of the Fire Station, will hold offices and meeting rooms to serve 500 employees, totaling about 12,000 square meters of floor space. Access to the offices in both the new building and the renovated one will be from the courtyard atrium space. Staircases to the plaza level and underground 300-car capacity parking garage are dramatically contained within the two giant concrete cores that support the new structure, while a lift battery is integrated in the drying tower of the former fire station to provide easy access across the floors. The super cores, which also enable circulation, are not unlike the double-duty extrusions that lift the Phaeno Science Center which Zaha Hadid Architects completed in 2005. Like the Science Center, the new Port House addition hovers above the ground, opening up a plaza space below.

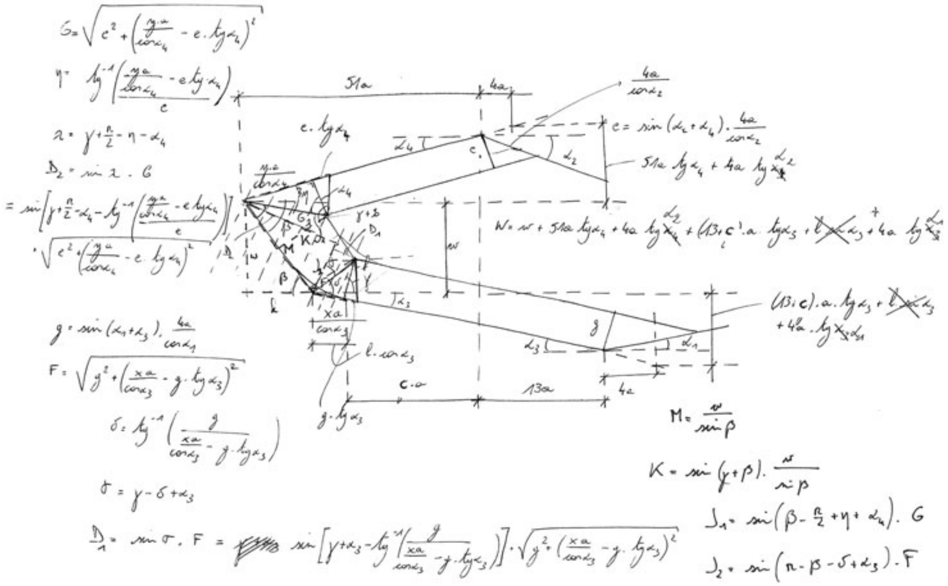
The original concept changed very little after the competition phase of the design process aside from the number of supporting cores on which the new structure rests (which shifted from three to two.) The team had already determined during the competition phase that the structure should change from all steel to a combination of steel and concrete; the main supports



12.3 Building sections illustrate the super cores and cantilever. Zaha Hadid Architects, Studieburo Mouton, Port House, Antwerp, Belgium, 2015.

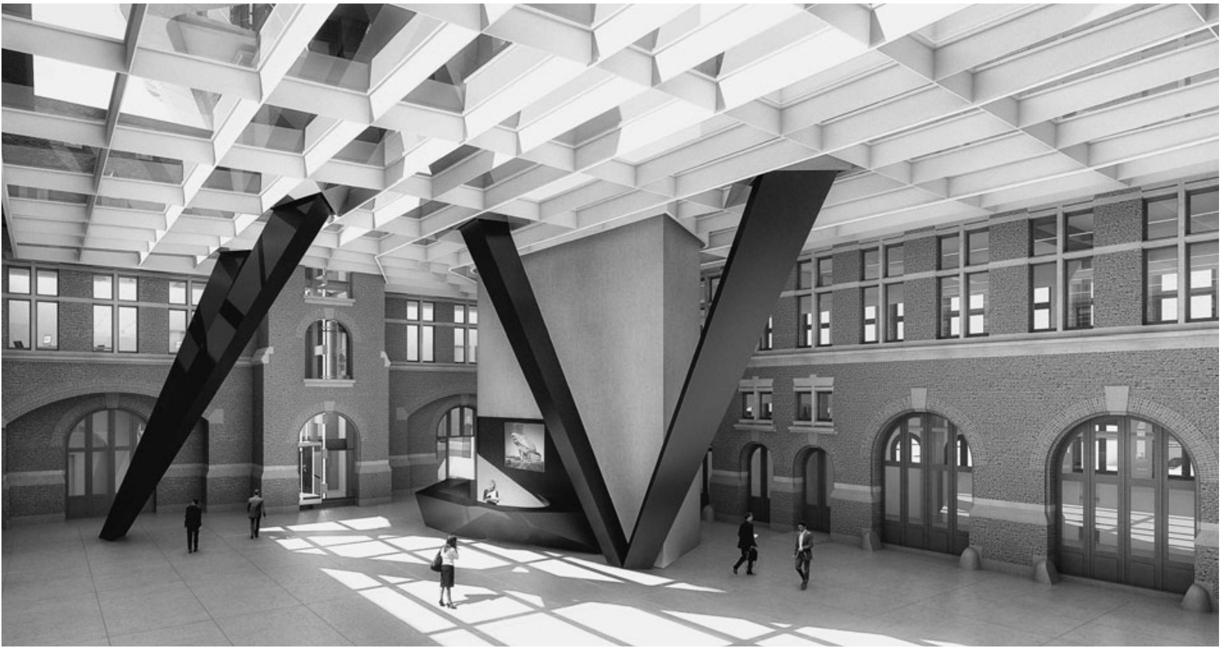
Courtesy of Zaha Hadid Architects.

and bridge are concrete, supporting three, three-story-high steel trusses that frame the cantilevered bar. Mouton describes the structure for the building as "a ring of concrete made by the bridge, the foundations and the concrete circulation cores. Additionally, four steel tubes that are configured like an open paper clip of 50 meters long support the volume and provide stabilization for the wind load." Mouton goes on to say that "Joris and Zaha Hadid Architects commented on the structure throughout the process to clarify their design intent. During this close collaboration, the architectural form finding in return was informed with sound structural logic."[5]



12.4 The design approaches were a combination of analogue and computation techniques. The calculations by BB describe the rationalization process of the façade geometry. Zaha Hadid Architects, Studieburo Mouton, Port House, Antwerp, Belgium, 2015.

Courtesy of Zaha Hadid Architects.



12.5 The structural form enables an open plaza below. Zaha Hadid Architects, Studieburo Mouton, Port House, Antwerp, Belgium, 2015.

Courtesy of Zaha Hadid Architects.

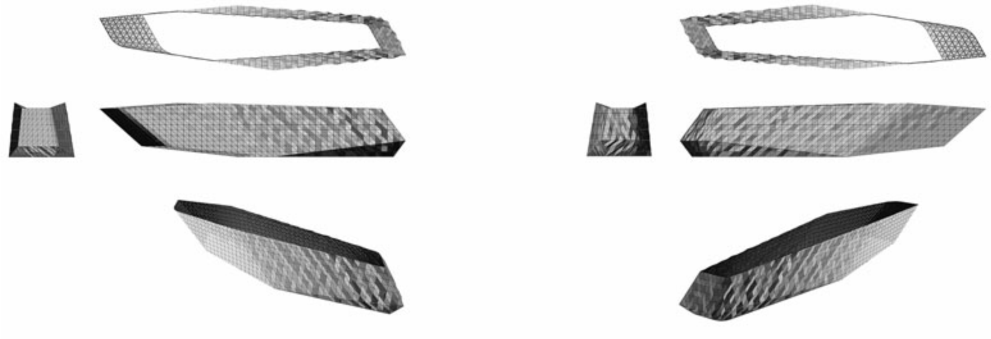
Evolution of the Façade: BIM and Prefabrication

In the *Architectural Design* magazine article, "Arguing for Elegance," Patrick Schumacher generally describes the kind of thinking that seems to have contributed to the design of the Port House façade and to its ultimate rationalization for construction. "As ordered complexity, the elegant composition is highly differentiated, yet this differentiation is rule governed, based on a systematic set of lawful correlations that are defined between the differentiated elements and subsystems. Such correlations integrate and (re-)establish a visible coherence and unity across the differentiated system."[6] Influenced by Antwerp's diamond trade, the Port House façade envisaged by Zaha Hadid Architects uses translucent and reflective glazing to create a shimmering, diamond-like effect. The glimmering exterior is visible from great distances and also enables panoramic views from inside the open, expansive interiors. The crystal façade geometry is achieved by pushing and pulling points of the triangular façade panels from its planar surface.

Gert Biebauw, Project Architect at Bureau Bouwtechniek and member of the project team from the start of the competition, understood ZHA's design concepts—their evolution and rationalization for construction. Bureau Bouwtechniek pushed for Building Information Modeling (BIM) and prefabrication, which were key to facilitating this process. In the initial competition phase realized through a Grasshopper model, every triangle of the façade was a different size and had a unique placement. Biebauw explains that "One of the biggest challenges

12.6 The triangulated façade system provides a diamond-like effect, alluding to Antwerp's diamond trade. Zaha Hadid Architects, Studieburo Mouton, Port House, Antwerp, Belgium, 2015.

Courtesy of Zaha Hadid Architects.



12.7 The triangulated, panelized façade will be prefabricated and shipped by barge to the site. Zaha Hadid Architects, Studieburo Mouton, Port House, Antwerp, Belgium, 2015.

Courtesy of Zaha Hadid Architects.

was how to achieve the façade design within the constraints of the budget and constructability."[7] Bureau Bouwtechniek rationalized the design by limiting the number of façade panel types and the distances they pull away from the façade plane by setting three fixed distances. These modules were then carefully composed to create the aesthetic envisaged by ZHA, "but helped to explain the seeming randomness to the contractors. This way, apparent randomness is contained within constructible boundaries,"[8] says Biebauw.

BIM was crucial to the rationalization process that actually began with physical modeling. Biebauw describes how "Rhino and Grasshopper helped facilitate the design, but in order to understand the design for constructability, we made physical models—cardboard models—to help to understand what's happening in the Rhino model before moving into Revit."[9] Pauwels was also fully on board with the conversion to Revit, saying that more and more projects at Zaha Hadid Architects are being facilitated through BIM. According to Pauwels,

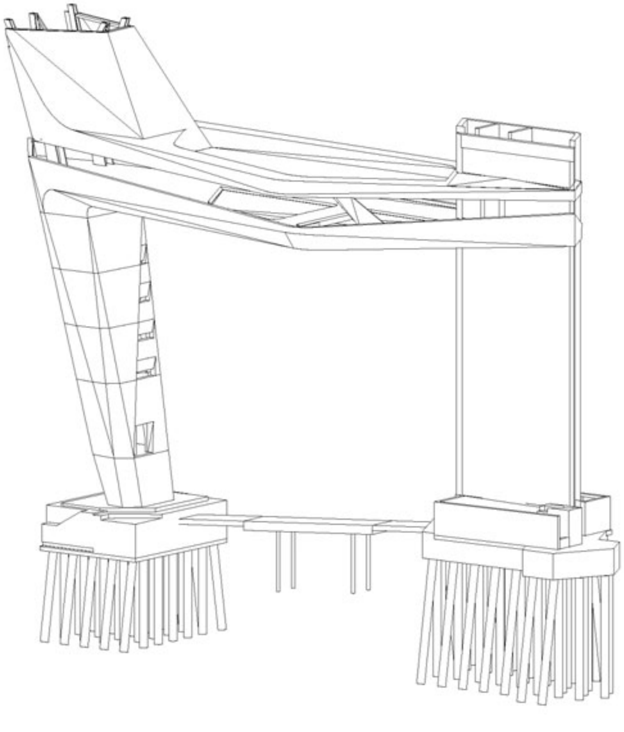
> Obviously BIM is the way forward and if implemented across disciplines can work extremely efficiently, both during the design process and with the contractors throughout construction . . . Some of the advantages of having a good Revit model are that one can easily extract data for cost calculations and project planning; that you detect clashes between disciplines early on in the design process; that you have a clear basis for the tender and an easy means of checking information from the contractor, etc.[10]

The contractor was asked to also integrate services into the Revit model, which originally contained only the architectural and structural information.

Striving for ease of construction and meeting their budget targets for the Port House, architects, engineers and fabricators pushed for prefabrication on a number of components of the design, reducing costs and minimizing the risk of delays due to bad weather. The steel cage, triangulated façade and roof atrium will be constructed in larger, transportable components off site. Victor Buyck Steel Construction, the steel subcontractor, drove the decision to divide the 1000-ton steel cage into six huge parts. The components will be transported over the river Schelde, placed in position by crane, and welded together on site. This fact reveals some of the challenging aspects of prefabrication: transportation of parts to the site and movement of parts once on site. Minimizing the amount of time that a crane is needed helps to maintain the cost benefits of off-site construction. For the Port House, a crane will be used to place the steel cage, the atrium and façade components. The triangulated façade will be partially constructed off site into configurations of four triangles, which are framed in 4 meter × 8 meter modules. Biebauw describes the façade system as "a giant puzzle and challenging to assemble because each piece will deflect with loads, so in the air, there aren't fixed points since there is no load yet."[11] Nevertheless, the benefits to prefabrication include reduced on-site construction labor costs and shortened construction schedules, which outweigh the costs of planning at the front end of the job.

Construction Process

The construction sequence began with site excavation, construction of the underground parking garage and the foundation. The two concrete "legs" will be formed and topped off by the prefabricated steel cage and façade. Concurrent with construction process at the site, the



12.8 The structure and construction sequence are illustrated through this drawing of the foundation, super cores and bridge, which support the new addition. Zaha Hadid Architects, Studieburo Mouton, Port House, Antwerp, Belgium, 2015.

Courtesy of Zaha Hadid Architects.

design team worked with fabricators to create mock-ups for various systems at a range of scales from the concrete pillars to façade prototypes. The componentry and details derived from close collaboration among architects, engineers and fabricators. Existing ZHA projects, as well as the fabricator's off-the-shelf systems, were mined for design details and constructability, but the two main design concepts for the exterior, the cores and textured façade, are essentially new inventions that required a lot of testing and research. Zaha Hadid Architects' collaborative model (working with engineers and fabricators) and emphasis on research contribute to ZHA's demonstrated capacity to construct buildings at the forefront of contemporary architectural design.

Since the competition, the client requested a number of changes to the brief. Pauwels describes that "A 'very good' BREEAM [British Research Establishment Environmental Assessment Method[12]] target was set only during the detailed design phase. Similarly, it was decided later to follow ABO (Activity Based Office[13]) principles, which had a significant impact on the layout of the open plan offices and the required number of meeting rooms. Another change to the initial brief was the decision to double the size of the required underground car parking."[14] The project has already received a "very good" rating from BREEAM based on the

12.9 The Port House is scheduled to be completed in 2015. Zaha Hadid Architects, Studieburo Mouton, Port House, Antwerp, Belgium, 2015.

Courtesy of Zaha Hadid Architects.

design and a certificate will be issued after the project is completed. Pauwels describes that some of the sustainable measures include geothermal "borehole energy across the site and the inclusion of a substantial number of docking stations for electric cars. In the existing building we are working with chilled beams, while in the new building we opted for a solution [for thermal comfort] with chilled ceilings."[15]

Despite the changes in the program and the challenges of optimizing the form for construction using new technologies and techniques, the project is scheduled to be completed on time and budget in 2015. The fast-track design-build process has enabled a 33-month construction schedule, partly facilitated by the conversion to BIM and prefabrication for large areas of the building. On the whole, the Port House project is a textbook example of the benefits of collaboration and technology when constructing complex form and structure. Pauwels agrees, saying, "A project succeeds or fails with collaboration and communication. The importance of communication within a design team and with a client body is often underestimated."[16]

Notes

1 Guy Mouton, Interview by authors, phone interview, Belgium, June 5, 2013.

2 Guy Mouton, *Designing Together*, Gent: Witte Zaal, 2009.

3 Zaha Hadid, "AA School of Architecture – Lectures Online," AA School Homepage, http://www.aaschool.ac.uk/VIDEO/lecture.php?ID=1951 (accessed March 18, 2014).

4 Joris Pauwels, Interview by authors, email interview, Zaha Hadid Architects, March 17, 2013.

5 Mouton, Interview.

6 Patrik Schumacher, "Arguing for Elegance," *Architectural Design*, 77(1) (2007): 28–37.

7 Gert Biebauw, Interview by authors, phone interview, Belgium, May 30, 2013.

8 Ibid.

9 Ibid.

10 Pauwels, Interview.

11 Biebauw, Interview.

12 BREEAM in the UK is very similar to the LEED or Leadership in Energy & Environmental Design rating system, which is the dominant environmental ratings system in the US.

13 ABO is a relatively new concept for office design in which an open plan encourages collective work and meetings while also saving costs on individual workstations.

14 Pauwels, Interview.

15 Ibid.

16 Ibid.

– 13 –

Tools for Collaboration

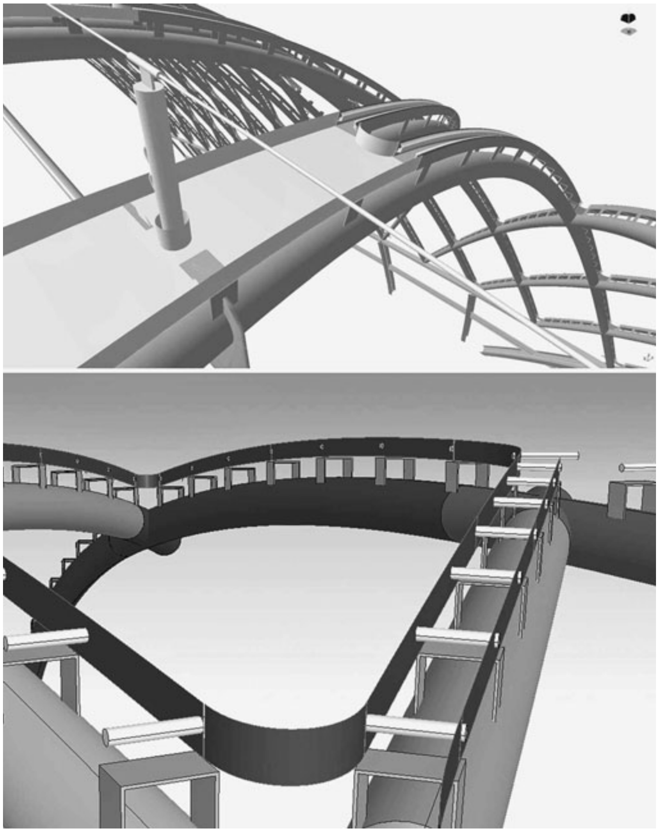
Architect, urban designer, educator and the late Dean of Architecture at MIT, Bill Mitchell is famously quoted as saying, “Architects drew what they could build, and built what they could draw.” As software that facilitates representation, rationalization, analysis, design, prototyping, component fabrication, and construction becomes ever more available, ever more widely used, and ever more cross-platform compatible, what an architect can draw and build has grown and shifted. Software tools with one, some, or many of these applications are increasingly a vehicle for collaboration among architects, engineers, contractors and owners (the AECO community). Collaborators find greater coherence and integration when communicating often and this certainly happens through numerous means: from verbal communication about the values and goals for a particular project to a highly intricate cloud-based virtual model that integrates all building systems. Increasingly, as emerging software becomes more accessible and easier to use, digital tools have a significant role to play, potentially addressing a number of the challenges to architect–engineer partnerships, and making teamwork more efficient and integrated.

Representation and Rationalization

Perhaps the most obvious tools for any designer are the tools of representation. Given the centrality of documentation to the professions, it is understandable that software for representation proliferated in both fields. Recognizing the complexity of contemporary design and practice, clear and consistent visual communication is crucial to project development and realization. This is true throughout the entire project, from the initial stages when designers use hand sketching and form-finding, through analog and digital techniques, and of course, in the form of construction documents. Different types of representation are required depending on the audience: the owner might respond better to a rendering than a wall detail, whereas contractors, fabricators and permitting agencies usually require wall details and a whole lot more.

Certainly, most engineering and architecture practices have long shared 2D digital drawings using AutoCAD and similar programs. However, increasingly in collaborative design, practitioners cite the importance of 3D digital representation tools such as Rhinoceros (Rhino) to their conversations and mutual development of design ideas.[1] This shift is in part to facilitate communication at an earlier stage in design, but also to take advantage of the generative potentials of the software in developing form. Architects and engineers alike are transforming the practices through digital tactics. George Keliris, structural engineer in Buro Happold's London office, remarks that their tools and techniques have radically changed in recent years. Whereas visualization was usually left to the architectural designers, the engineers at Buro Happold have integrated the tools into their working methods, helping to conceptualize complex, efficient structures in shorter lengths of time.[2]

Contemporary use of design software often necessitates digital methods for rationalizing form as components that can be easily fabricated and assembled. An example of this process is demonstrated in the case study of the ARTIC project (see Chapter 9) where rationalization of the curvilinear form into constructible components was a challenge facilitated through the use of Grasshopper, a visual scripting software plugin for Rhino, and CATIA[3] which permits modeling, scripting, data management and fabrication of complex forms.



13.1 The digital models for The Anaheim Regional Transportation Intermodal Center (ARTIC) were generated in various software including Catia and Grasshopper. PB/HOK, Buro Happold, Anaheim, California, 2014.

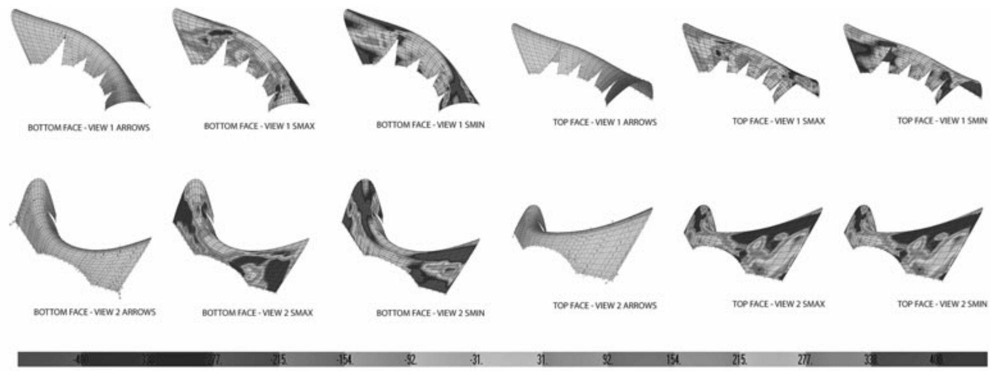
© Buro Happold.

Rationalization and Analysis

Because complex shapes need to be understood not just in terms of geometric resolution, but also in terms of strength, deflection and other performance criteria, architects and engineers employ a wide range of robust software for rationalization and analysis. These parametric tools include the already mentioned Grasshopper and CATIA, and finite element analysis (FEA) programs such as ANSYS and SAP2000 that can analyze multiple performance criteria (stress, deflection, thermal performance, air flow). Digital visualization and analysis tools have forever changed the practices of architecture and engineering. Ben van Berkel of architecture firm UNStudio, writing with the practice's Smart Parameter Platform, states, "It is clear now that computation is ubiquitous, and form making and form controlling are no longer its most expedient uses. Whether it is through proprietary and customized software or a single piece of code, computation's primary potential lies in its flexibility to communicate design across multiple disciplines via associative data."[4]

Similarly, architects and engineers Besserud, Katz and Beghini at SOM, a noted collaborative practice, say the use of computational algorithms facilitates collaboration, particularly in design processes that require architects and engineers to "jointly define performative goals and constraints," for example where complex shapes need to be geometrically defined and technical feasibility needs to be tested for multiple design approaches:

> Algorithmic tools . . . are critical to expediting processes of searching vast solution spaces for well-performing designs, and are facilitating the exploration of new, previously inaccessible theoretical paradigms and emergent formal typologies . . . In addition to the meshing and solving capabilities of commercial FE [Finite Element] programs, the visualization of data is another valuable capability, especially with regard to reinforcing transdisciplinary collaborations between architects and engineers.[5]



13.2 Syracuse University Shells Structures course student collaborative final project showing SAP 2000 analysis.

© Goldman, Ingersoll, Lipezker, and Solomon.

Digital applications are powerful collaborative tools, and they can facilitate more productive conversations between architects and engineers, in particular when they allow engineers to quickly communicate the technical implications of specific design decisions, and help refine their architectural collaborators' understanding of the engineering constraints and opportunities. According to Besserud, Katz and Beghini:

> With visual mappings of the flows of the forces and coloured heat maps that depict the distribution of stresses and magnitudes of displacements, architects can immediately develop a powerful intuitive understanding of how the overall shape of a building affects its structural nature, even without a solid understanding of the mathematics or algorithms. This ability to get a clear window into the structural performance of a given design scheme allows designers to speculate more intelligently and more immediately about possible modifications to improve the design.[6]

Of course, analysis software has proven crucial from a material efficiency standpoint as well. Ken Sanders of prominent architecture firm Gensler describes the extraordinary benefits of analysis software to provide design feedback, resulting ultimately in tremendous cost savings in construction. In Gensler's Shanghai Tower, for example, the wind load is a primary concern, and has a large impact on the twisted structure, which is 2,073 feet tall. Structural engineers at Thornton Thomasetti used digital tools to rationalize the form, which includes 14-story atria along the façade that require "double curtain wall boomerang trusses at the floors." Sanders remarks that digital analyses enabled the collaborating team to streamline the design, saving an estimated $50 million.[7]

Building Information Modeling (BIM)

In addition to advances in computation, visualization techniques, and FEA software, Building Information Modeling (BIM), which enables teams to create comprehensive shared digital models, is also revolutionizing the collaborative design process. BIM software applications are parametric tools that facilitate design and representation through relational data driven models. When these models are shared across multiple disciplines, design teams can more easily asses the impacts of integrating systems and monitor the consequent effects of changes to the design.

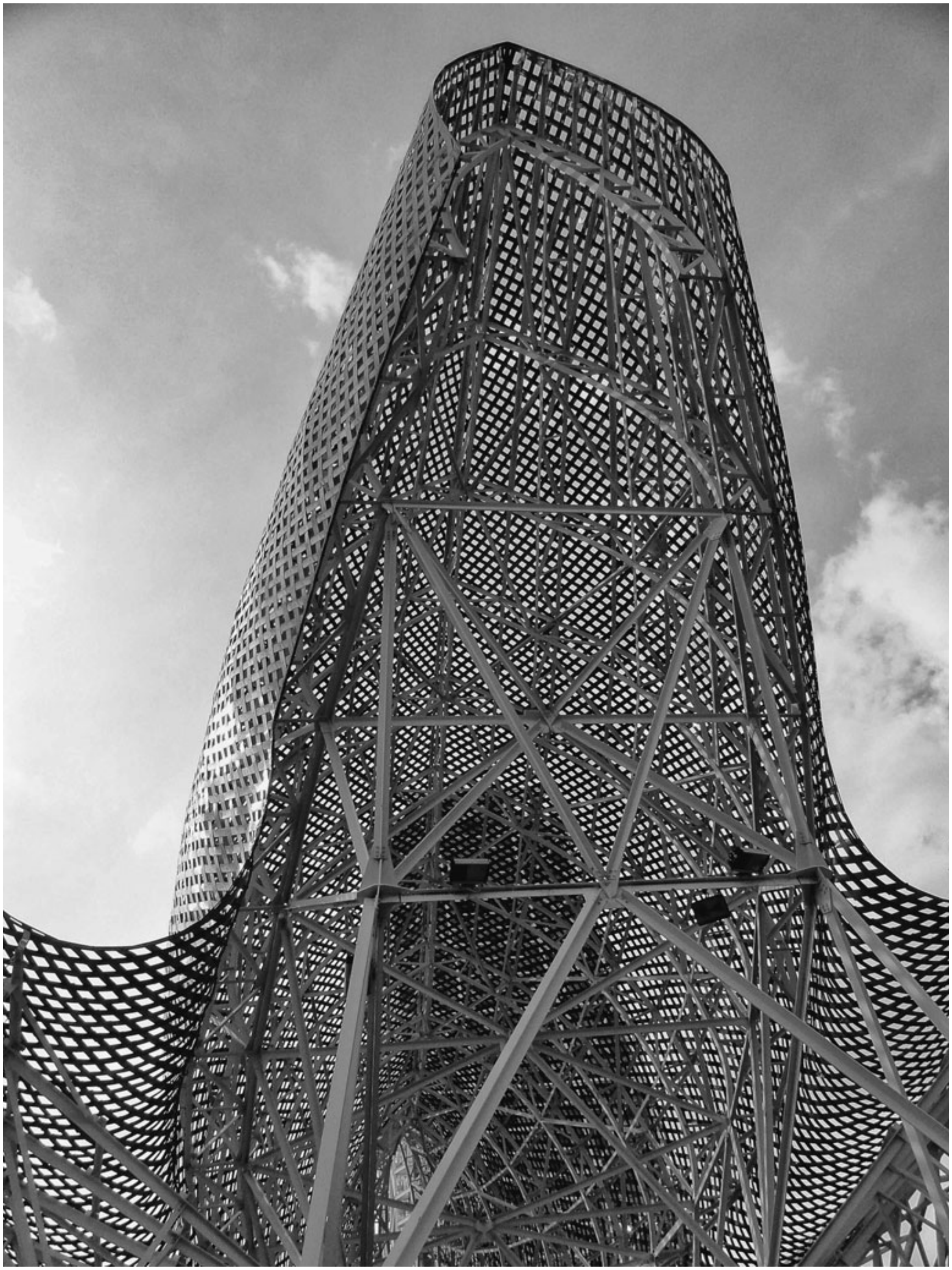
Although BIM has only recently become widely used, the software has roots as far back as the 1960s with super computers that enabled graphical visualization through algorithmic computation, seen first in Ivan Sutherland's Sketchpad program.[8] In the 1980s, computer scientists created object-based parametric models.[9] Through development over time, the capabilities and user interfaces improved, and the software also became more affordable. (Some of the first 3D modeling software licenses cost $35,000 per person.[10]) Today, a host of BIM software applications have flooded the market, including Digital Project, Tekla, ArchiCAD, Bentley Architecture, and Revit.

In architectural practice, BIM has gained rapid popularity, sparked in part by one of the first projects to propel relational object modeling into the mainstream, the Guggenheim Bilbao, completed in 1997, designed by Gehry Partners and structural engineers at SOM, which was met with world-wide popular acclaim.

Gehry's firm first used aerospace engineering software CATIA to develop construction documents and program fabrication machines for the Fish Sculpture at the Barcelona Olympics in 1992. After using the software for ten years with great success, the firm created a research, software development and consulting firm, Gehry Technologies in 2002. They modified CATIA to create Digital Project, their own BIM software, for use in the AEC industry. Gehry Technologies provides consulting services to other design firms for the development and management of BIM models. For example, Diller, Scofidio + Renfro contracted Gehry Technologies to manage the digital model on Tully Hall at Lincoln Center in New York City. Ben Mickus, Project Manager for DSR at the time, argues that the software was an essential component of the collaboration and integration of the project.[11]

In recent years, numerous industry practitioners have converted their work flow processes to include BIM, if not from the beginning of the project, then for the development of the construction documents, since multiple drawing types are automatically generated in the BIM template. Practitioners using BIM later in the design development process use workflows that initially involve other analog or digital means such as drawing and digital form-finding through software such as Rhino. Once design ideas are more solidified, the Rhino geometry is exported to become the basis for the BIM model. Some designers feel that Rhino and other NURBS (non-uniform rational b-splines) based software allow for more agility in terms of formal development since BIM compels decisions about materials and systems, which are not necessarily ready to be selected in the early stages of design. Yet others, including Danelle Briscoe, author of "Beauty + the BIM," recognize that BIM provides fertile ground for design practices driven by the logics of materials and systems. "With conceptualization through BIM, the information becomes a recipe for exchange of aesthetics (among other things) . . . The open-source nature of information exchange means design of built space and form can be improving exponentially as a collective for a progressive process, "[12] says Briscoe. She emphasizes the importance of design leadership to guide decisions in collaborative models as a way of overcoming the mediocrity associated with normative uses of the software.

In addition to the positive implications for design and collaboration, another of the most significant advantages of BIM is the potential for cost savings in construction. Using BIM in the design process can be costly for firms at the front end (associated with staff training, software acquisition, and time invested in detailed modeling). But in any design project, construction accounts for the bulk of the budget and BIM can translate into significant cost savings during construction if project managers coordinate systems input from each discipline (clash detection) and use the software for scheduling and cost estimating. Some municipalities also provide code assessments of the BIM model at multiple stages of the design. Through better integration of



13.3 The fish sculpture was Gehry Partners' first foray into the use of CATIA for design and fabrication, Barcelona, Spain, 1992.

© François Philipp.

systems and codes, BIM offers an opportunity to reduce errors and waste. The software's remarkable 4D capabilities permit users to associate building components with project phasing, enabling the virtual model to be used to simulate construction and facilitate project scheduling. The software also simplifies cost estimating (referred to as 5D), helping designers and contractors to align the project with the budget. Phil Bernstein, Vice President of Autodesk says, "There is ten times more money in building as there is in design so [practitioners] are focused on making building more efficient."[13] He believes that "This is the last great professional battle ground," suggesting that architects, especially, need to be proactive about asserting their role in the design and construction process and exploiting BIM's capabilities, as one way to get ahead of the curve.

Some industry professionals are using BIM models to facilitate Lean Construction (a project delivery method that emphasizes better scheduling and cost estimates, discussed in greater detail in Chapter 14). Interviewed in *Architecture*, Seattle architect Joe Pinzone extols the benefits of determining systems locations prior to construction: "One of the dirty little secrets of construction is how much re-work has to be done . . . Moving something three times is built into the cost of that sprinkler head."[14] Ultimately, a carefully managed BIM model translates into both cost savings as well as a reduction in on-site waste. The American Institute of Architects (AIA) carried out a study of the emerging alternate contract type Integrated Project Delivery (IPD) which often makes use of BIM. One of their case studies was the Cathedral Hill Hospital in San Francisco. There the team located all the studs in the model so the handrail could be attached directly. And since a hospital has handrails along almost every foot of the corridors, the elimination of the continuous backing for the handrail saved $400,000 on total project costs.[15]

A further illustration of cost saving can be found in a project at the Stanford University Medical Center. Three Cath Labs of similar size and scope were designed and built. The first lab was constructed based on 2D digital drawings. The second two labs were designed by Design Partnership LLP Architects and Planners who used BIM for some of the documentation process of the second and for the entire development and documentation of the third. In analyzing the differences and successes of the three projects, the owner-architect team discovered that the first lab, designed using traditional methods, had change orders[16] that totaled 12.4 percent of total costs whereas the 100 percent BIM project had change orders below 0.1 percent of total construction costs! They also discovered that the BIM project saved 23 percent on total costs, had 44 percent fewer requests for information (RFIs) and was completed 35 percent faster.[17] Given the ability to integrate systems and design projects holistically, it is no surprise that the use of BIM is rapidly gaining popularity industry-wide.

BIM's advantages extend far beyond cost and workflow efficiencies in design and construction: potential benefits accrue through the working life of a building if the model is used as a building management tool to facilitate maintenance, additions and day-to-day management of building systems. Investing in the accuracy of the model makes sense for long-term building maintenance goals[18] especially in large, institutional projects. Arnold Lee of HOK notes, "Almost all of our clients need a virtual database for record keeping and maintenance and so it's not uncommon to deliver a digital model at the end of a job . . . So our consultant teams need to be fully digital."[19] A number of software engineers are developing BIM tools for life-cycle assessment. Shaun Farrell, Practice BIM Manager at Zaha Hadid Architects (ZHA), describes the potential of BIM models to maximize the utility of environmental control systems: "The next step on the mechanical side is to look at intelligent building systems where we have sensors that are attached to the real-world object, and the sensor reports back to the building model so that the operators can see graphically how the building is functioning."[20]

Designers at firms such as Kieran Timberlake, SOM, and Foster + Partners, are also working on life-cycle assessments. By evaluating the performance of systems, designers can determine their success and viability for future projects. Project Dasher, for example, "is an Autodesk research project using a BIM-based platform to provide building owners with greater insight into real-time building performance throughout the life-cycle of the building."[21] Since many sustainability technologies are new to the market, the assessment tools are essential to evaluation and making building systems more sustainable and more efficient. The branch of the United States government responsible for federal buildings, the General Services Administration, is pushing for adoption of BIM technology across its facilities for data collection, more fine-tuned building system management, energy savings, more efficient building maintenance and renovation, and the improved working environments that it can support.[22] Farrell at ZHA reports that the government in the United Kingdom has mandated use of BIM for all government public works projects by 2016 and that in the US, the Army Corps of Engineers is "all over it like a rash."[23]

As a result of the many advantages described, use of BIM software has grown markedly in recent years. A McGraw Hill Smart Market Report found in 2012 that 71 percent of architects, engineers, contractors and owners claim to use BIM on at least some of their projects, which represents a 75 percent increase over five years.[24] Despite this growth, the software is not without controversy. Criticism of early versions of the software was that it was a kit of "object" parts that proved very challenging to manipulate for customized design work. The softwares' libraries of materials and components have inherent benefits and limitations—BIM programmers cannot possibly provide every system available in construction. Furthermore, the databases can be challenging to manipulate when designing customized systems. The various BIM tools continue to evolve, however; not only are the interfaces becoming more user-friendly, but translation between design and production software has also become easier. As already described, for more innovative and non-normative structures, many designers begin the design process in "looser" programs such as Rhino, Maya or even Sketchup and then import the geometry into a BIM model to serve as a basis for development of the details and constructability. Farrell at ZHA is looking at the strategic side of workflow to change the way in which the office uses Revit (one of the most popular BIM tools) since the program is not as flexible as his team would prefer, particularly when processes for evolution haven't been embedded in the model. He's investigating how to shorten the cycle of conversion between the ideas in the design models and the production models in BIM.[25]

Other drawbacks to current BIM use include transition to new working methods, the inter-operability of different systems between different design partners and firms, and the relative precision of the digital versus the reality of real-world construction processes. Joris

Pauwels of ZHA reports, "The main challenge is ensuring how the model is to be used by all parties involved and agreeing on procedures for review of contractor proposals."[26] Designers, engineers and contractors don't always have a shared BIM model and aren't always using the same software. In those cases, firms like Foster + Partners have a strong handle on making whatever software is used a smooth transition. Describing that process, Xavier De Kestelier, a Partner and joint head of the Specialist Modeling Group, said, "The way we work is to always try to make sure that whatever modeling strategy there is, you keep it software independent. We use a 'geometric method statement', which is a recipe for building the geometry that you could use to draw it by hand. Since everybody has their own software, with the recipe, everyone can build their own geometry."[27]

Stephen Kieran and James Timberlake advocate that an accurately constructed building "simulation" where dimensions can be derived from the 3D model will transform working methods, "rendering the once necessary dimensional drawings now obsolete."[28] In response to this idea, Dan Willis and Todd Woodward point out that if construction documents go by the wayside, "there will be unprecedented demands for accuracy of the architect's computer modeling, but there may also be the potential for increased control over the built work."[29] They go on to caution, however, that the "virtual reality of the BIM is actually more precise than the material world . . . We believe that the inevitable 'errors' present in reality, including natural processes such as thermal expansion and weathering, make it impossible to achieve a *direct* correlation between digital data and a constructed building."[30] In most projects, however, which are not entirely machine-fabricated, the finishes and materials that are made by hand, like the paint on the drywall, provide opportunities for field adjustments when the real-world conditions don't match with the virtual construction.

Despite the challenges associated with BIM modeling, the associated productivity gains mean that the tool is certain to become an integral part of the collaborative process for architects and engineers. It is hoped that the tools will evolve to facilitate earlier and more integrated collaboration amongst all the AEC disciplines. Harif Kara, founder and director of famed engineering collaborators AKT cautions, "[T]hese new media should also be approached cautiously since the ubiquity of digital media cannot replace human interaction that frames new questions and permits interdisciplinary creativity."[31] For a more in-depth discussion of the humanistic aspects of collaboration, please see Chapter 2.

Frontiers in Fabrication

THROUGH the advancement and proliferation of digital fabrication machines, architects and engineers are reconnecting with the craft of making. As noted previously, constructability of complex forms drove Gehry and Partners to use CATIA to communicate with fabricators. Architect William Massie describes how digital tools are allowing more direct contact between the designer and the designed: "The utilization of digital information systems, the concept of information moving through the use of digitally controlled processes—bits to atoms—allows the individual to move directly from abstraction to object without typical mediation,"[32] thereby making the construction process more efficient. Traditionally, the "middle man" at the fabrication shop interprets the 2D drawings in the form of shop drawings, which are then confirmed by the architects or the engineers. All around, it's a time-consuming process and one that can be avoided if designers are willing to invest in a fabrication-ready model and can find manufacturers who have the know-how to efficiently interpret the digital files. Examples of such digitally driven fabrication include robotics, 3D printing, laser and water jet cutting. Bruce Gibbons of Thornton Tomasetti says the structural engineers in the office are taking advantage of the ability to fabricate components from BIM: "We've done quite a number of projects where we've provided Tekla drawings for the fabricators and [unlike other working methods] there are no disclaimers with this—the model can be used as a shop drawing."[33] This process can be especially efficient when used in combination with prefabricated or modular construction, which has proven to reduce construction schedules, waste and costs (see the B2 BKLYN case study in Chapter 5).

Except in rigorously designed prefabricated and machine manufactured projects such as the Camera Obscura by SHoP Architects, which was entirely digitally fabricated and assembled as a kit-of-parts, inefficiencies pervade traditional construction processes, and it seems likely they will continue to do so. Tools such as digital fabrication machines and parametric software, and processes such as new project delivery methods and prefabrication, are revolutionizing the construction industry, but considering how long many of these technologies have been commercially available, the change is slow in coming.

Architectural journalist Brian Libby points out that it takes 11 days for the airplane manufacturer Boeing to construct a "Next-Generation 737. Meanwhile, constructing even a small house can take months, but integrated project delivery stands to make the design industry more efficient . . . [A]rchitecture remains among the most costly and time-consuming of human endeavors."[34] New and emerging forms of project delivery methods for architectural and engineering projects are discussed in the next chapter. These innovations, such as Integrated Project Delivery, may be what will speed up industry-wide adoption of new software and fabrication tools and maximize their collaborative potential.

Notes

1 For example, Hans Schober, Interview by authors, Skype interview, Stuttgart, June 19, 2013; and George Keliris, Interview by authors, phone interview, London, UK, June 21, 2013.

2 Keliris, Interview by authors.

3 CATIA, or Computer Aided Three-Dimensional Interactive Application, was created by aircraft manufacturer Avions Marcel Dassault in 1977, and it has since become popular in other manufacturing industries as well as architectural and engineering offices.

4 B. van Berkel, "Navigating the Computational Turn," *Architectural Design*, 83 (2013): 82–87, p. 87.

5 K. Besserud, N. Katz, and A. Beghini, "Structural Emergence: Architectural and Structural Design Collaboration at SOM," *Architectural Design*, 83 (2013): 48–55.

6 Ibid.

7 Ken Sanders, "Collaboration & Performance/Materials & Building Practices," Lecture, New Constellations, New Ecologies for Association of Collegiate Schools of Architecture, San Francisco, CA, March 20, 2013.

8 Harry Henderson, *Encyclopedia of Computer Science and Technology*, New York, NY: Facts On File, 2003, p. 463.

9 Charles M. Eastman, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, 2nd edn., Hoboken, NJ: Wiley, 2011, p. 25.

10 Ibid., p. 28.

11 Ben Mickus, Interview by authors, in-person interview, San Luis Obispo, CA, March 15, 2013.

12 Danelle Briscoe, "Beauty + the BIM," ACSA 100th conference, Boston, MA, 2012.

13 Philip G. Bernstein, "Case Studies of Design Innovation," Lecture, New Constellations, New Ecologies for Association of Collegiate Schools of Architecture, San Francisco, CA, March 20, 2013.

14 Brian Libby, "Plugging In," *Architect the AIA Magazine*, January (2013): 80–86.

15 AIA, AIA Minnesota, School of Architecture—University of Minnesota, "IPD Case Studies," www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab093703.pdf, p. 21 (accessed March 18, 2014).

16 "Change orders," as they are called in the AECO industry, are changes to the scope of work agreement, discovered after the project has been bid and priced, translating to added total costs (beyond the expectations) for construction of the project. A 2006 AIA survey found that change orders averaged about 4 percent of total construction costs, although the survey found that in 23 percent of the jobs reported, change orders amounted to 5 percent or more of total construction costs. Change orders are caused by a range of circumstances: owners modify the scope of work after the bid, architects and engineers make mistakes on the original documents (RFI responses can result in change orders), and unpredictable circumstances arise. The cost of change orders depends on the scope and scale of the work, and regional costs of construction also play a large role. See Kermit Baker, PhD, Hon. AIA Chief Economist, "AIArchitect This Week | Economics: WORK-ON-THE-BOARDS SURVEY: Firms Enjoy a Late Summer Surge," http://info.aia.org/aiarchitect/thisweek06/0922/0922b_otb.cfm (accessed March 18, 2014).

17 Eric Peabody, "Experimental BIM Use Comparison on Stanford Hospital Cath Labs," Upload & Share PowerPoint presentations and documents, http://www.slideshare.net/epeabody/shc-cath-7-9-10-comparison (accessed March 18, 2014).

18 Eastman, *BIM Handbook*, p. 21.

19 Arnold Lee, Interview by authors, phone interview, San Francisco, CA, May 30, 2013.

20 Shaun Farrell, Interview by authors, in-person interview, London, December 12, 2012.

21 http://www.autodeskresearch.com/pages/dasher (accessed March 18, 2014).

22 GSA, "Facility Management," General Services Administration, http://www.gsa.gov/portal/content/122555 (accessed August 23, 2013).

23 Farrell, Interview.

24 McGraw Hill Construction, "The Business Value of BIM in North America: Multi-Year Trend Analysis and User Ratings (2007–2012)," *SmartMarket Report*, McGraw Hill Construction, p. 1.

25 Farrell, Interview.

26 Joris Pauwels, Interview by authors, in-person interview, London, December 12, 2012.

27 Xavier De Kestelier, Interview by authors, phone interview, June 18, 2013.

28 Stephen Kieran and James Timberlake, *Refabricating Architecture*, New York: McGraw Hill, 2004, p. 61, quoted in Dan Willis and Todd Woodward, "Diminishing Difficulty: Mass Customization and the Digital Production of Architecture," in Robert Corser (ed.), *Fabricating Architecture Selected Readings in Digital Design and Manufacturing*, New York, NY: Princeton Architectural Press, 2010, pp. 152–167, p. 183.

29 Willis and Woodward, ibid., p. 183.

30 Willis and Woodward, ibid., p. 184.

31 Hanif Kara, "On Design Engineering," *Architectural Design*, 80 (2010): 46–51.

32 William Massie, "Remaking in a Post-Processed Culture," *Architectural Design*, 72(5): *Versioning*, London: Wiley-Academy, 2002, pp. 54–59, p. 56.

33 Bruce Gibbons, Interview by authors, phone interview, Los Angeles, CA, July 8, 2013.

34 Brian Libby, "Plugging In", *Architect the AIA Magazine*, January (2013): 80–86, p. 80.

– 14 –

Delivery Methods Facilitating Collaboration

Simply put, contracts define the roles and responsibilities of architects, engineers, contractors and owners (AECO) and guide the relationships and communication among the people involved. The hierarchical organization guiding project delivery has remained fairly stagnant since the turn of the twentieth century: traditionally, owners hire architects who manage the design, development and construction of the project. Recently, however, the industry has developed alternatives to normative project delivery methods with the goals of improving design, communication, schedules and costs through increased collaboration. In *The Demise and Rebirth of Professionalism*, Carl Saper points out that for Frank Gehry, the redesign of the firm's contract structures was more important than digital technologies for growth and success of the office.[1]

Without a doubt, delivery methods significantly affect a project team's ability to complete a successful project. This chapter describes traditional delivery methods and emerging collaborative modes and their potential to redefine the industry.

Traditional Method of Project Delivery

The AIA developed its first contract in 1888, the precursor to the project delivery mode and contract type that has dominated the industry for over a hundred years, Design–Bid–Build. Using this conventional family of contract documents, the owner/client signs two contracts: one with the architects and, after the design is completed, one with the contractors. It is possible for the architects and owner to develop the goals and schematic design for a project without consulting other experts. When consultants are hired (including civil engineers, landscape architects, etc.), the architects manage and orchestrate the design, development, and permitting processes. When the design is complete, owners often solicit multiple bids for construction from contractors. Generally speaking, the low bid is selected, especially in governmental projects where federal and state laws require selection of the "lowest qualified, responsive and responsible bidder."

As discussed in Chapter 2, however, depending on the circumstances of the project, consulting engineers and construction experts late in the design process can be costly, and quite possibly an adversarial process. Barbara Jackson, author of *Construction Management Jumpstart*, and Director of the Franklin L. Burns School of Real Estate and Construction Management at the University of Denver, describes the problematic aspects of the traditional system, asserting,

> We're addicted to cheap in this country [the US] and design–bid–build, the low bid mentality, is the worst thing that ever happened to us as an industry . . . Our industry (architecture, engineering, and construction) is so familiar with a reactive model of engaging with one another versus a proactive model . . . We're missing fundamental trust. Good people have been trained to do bad things for a very long time and it's not that we've intended to do bad things, but we have a system of planning, designing, and delivering building projects that incentivizes distrust, incentivizes not communicating, and incentivizes keeping information close to the chest.[2]

For these reasons, in recent decades, industry professionals have sought out new delivery methods, and the AIA, the main source for industry contracts, has developed three other contract families. According to a 2011 survey of firms' use of the four main contract types, 60 percent of respondents reported using Design–Bid–Build contracts, whereas 51 percent had one or more projects with Design–Build contracts (where the owner contracts with a single entity to provide both design and construction services), 42 percent had projects with Construction Manager as Constructor contracts (where a single entity provides construction services and oversight thereof) and 13 percent had projects with Integrated Project Delivery (IPD) contracts. IPD is the newest contract type: the first "true" IPD project, the Fairfield Medical Office Building, began in 2005 and the AIA officially released an IPD contract as well as other associated documents (including a BIM agreement[3]) in 2008.

Integrated Project Delivery Defined

Since IPD is an emerging type, the method is evolving and multiple approaches are considered IPD-like. Generally speaking, integrated project delivery is a multiparty agreement where the contractor is brought on board from the start of the design process. Other legal strategies that guide integrated project delivery include liability waivers, shared risk/reward, financial incentives tied to goals and fiscal transparency,[4] which IPD participants surveyed reported "had a positive effect on the teams' perception of trust and respect for project partners."[5] Although the AIA has an official IPD contract type, the organization defines the principles of integrated project delivery (with or without the official AIA-IPD contract):

> IPD is a method of project delivery distinguished by a contractual arrangement among a minimum of owner, constructor and design professionals that aligns business interests of all parties. IPD motivates collaboration throughout the design and construction process, tying stakeholder success to project success, and embodies the following contractual and behavioral principles . . . Contractual Principles: Key Participants Bound Together as Equals, Shared Financial Risk and Reward Based on Project Outcome, Liability Waivers between Key Participants, Fiscal Transparency between Key Participants, Early Involvement of Key Participants, Jointly Developed Project Target Criteria, Collaborative Decision Making. Behavioral Principles: Mutual Respect and Trust, Willingness to Collaborate, and Open Communication.[6]

One model of IPD, sometimes guided by a non-AIA contract, an Integrated Form of Agreement (IFOA), introduces an entirely new ownership entity that requires collaboration among the owner, architects, engineers and contractors from the start of a project. The limited liability company, or Single Purpose Entity (SPE),[7] is funded through terms set by the owner for the project budget and compensation for non-owner parties. This equates to shared risk (if shared is checked on the contract) and potentially shared rewards (via the SPE). When contractors are involved early in the design process, this also has the potential to reduce Requests for Information (RFIs), which traditionally can be a costly component of the construction process.

The industry has also developed a number of delivery methods to use in conjunction with contracts as a way to address the problems of cost-overruns and waste. These include Lean Construction techniques introduced to the industry in the early 1990s based on lean manufacturing as demonstrated particularly in the automobile industry's successful reduction of costs, time, waste and space; and Target Value Design (TVD), which "designates value, cost, schedule and constructability as basic components of the design criteria."[8] Lean Construction and TVD are often used in conjunction, where the value or project costs drive the design decisions from the very start of a project and value is assessed throughout each stage of project development. This way the project costs and differences in designers' versus contractors' cost estimations are aligned/realigned throughout the project (instead of after the bidding process as is the norm).

Perhaps because IPD and the associated working methods are so new, the IPD Case Study Executive Summary, carried out with the AIA by a team at the University of Minnesota, states, "It is becoming clear that there are very few 'pure' IPD projects."[9] A 2011 survey of IPD awareness found that 73 percent of the IPD projects did not use the IPD contract.[10] The case study research also found that motivations for IPD vary, but are often driven by *Technical Complexity*, and healthcare seems to be the most popular program type. Other drivers for IPD include *Market Advantage* (providing the parties with marketable expertise), *Cost and Schedule Predictability*, and *Risk Management* (through increased communication).[11] In advocating for IPD, Ryan Smith, Director of the Integrated Technology in Architecture Center (ITAC), describes the benefits:

> Integrated Project Delivery (IPD) takes the desirable elements of both design build's speed and information sharing and performance contracts, which emphasize outcomes via shared risk and incentives. IPD supports designers and constructors working collaboratively to provide preconstruction services including cost estimating and constructability reviews, thereby integrating the activities of each project team player with the others.[12]

Professionals across the industry recognize the potential of the collaborative methods. Speaking in 2009, Engineer and President of Sciame Construction, Joseph Mizzi noted, "having discussed this approach with many of the architects we work with—but having utilized only certain aspects of IPD in practice—we are cautiously optimistic here at Sciame that under the right circumstances, IPD offers a real opportunity to deliver high quality buildings faster and more cost efficiently by maintaining and expanding on the collaborative approach that a proper construction management process affords."[13]

Barriers to IPD Adoption

ALTHOUGH contractors, architects and engineers are generally positive about IPD, some in the industry have been cautious about the new methods. A summary of the 127 AECO respondents in the IPD Case Studies research describes the range of comfort in the transition to highly collaborative modes:

> Asked to rank how "collaborative project delivery affects project efficiency" on a seven point scale (–3 = negative, 0 = neutral, 3 = positive), all participants recognized the positive effect collaboration has on achieving project efficiency. That engineers' perception of collaboration's effect on efficiency was slightly less positive than contractors (1.82 and 2.79 respectively) seems to support anecdotal comments that the engineers struggled most with the transition to highly collaborative environments.[14]

The AIA survey also found that architects perceived the design process to be less positive than the others surveyed and "shifting their familiar roles and responsibilities to take input from non-designers was uncomfortable for some."[15] Jackson acknowledges that the new delivery modes require an entirely different way of working. "This is earth shaking for the design industry because nobody is accustomed to this, so psychologically, culturally, practically, educationally—it turns everything upside down."[16] Speaking from a construction management perspective, however, Jackson says,

> Personally, in my own experience with IPD, if it's done right from the very beginning then there are no downsides, but it takes commitment and it all starts

> with the client . . . The transition is very difficult: with the first roadblock everyone goes back to a silo mentality . . . To me, the key to all this is leadership. The critical skills of that leader are facilitation, communication, the ability to dialogue, investigate and discover solutions together.

This corroborates Kellogg School of Management collaboration researcher Leigh Thompson's observations: "[W]ith a few key insights and simple best practices, teams can dramatically improve their performance and generate a creative conspiracy."[17] Thompson describes those "best practices" to include establishing rules and a strong leader to guide discussions.[18] Incidentally, the AIA IPD case studies found benchmarks of IPD management strategies included *strong leadership* and *intensified planning/team building*.[19]

Given the complexity and multiplicity of the practices of architecture, engineering and construction, integrated project delivery and the associated methods hold extraordinary potential and should not be undervalued, especially in their capacity to facilitate collaboration through more productive, less adversarial, more cost-effective ways of designing and delivering projects. Ultimately, AEC professionals recognize that although design–bid–build has served the building industry for 125 years, it is an antiquated paradigm and the industry has suffered as a result. Jackson summarizes her hope for the industry:

> I say it as gently as I can but I tell everyone on my project teams: this project is not about you. This project is about this community, this organization of folks and what they produce. This is what I call "full life benefits." In hospitals, for example, the notion of what we're working to achieve here is faster recovery, lower rates of infection—that's what we're up to and it's not about you . . . But owners need to be willing to invest in that kind of value . . . I think our industry is one of the noblest industries on the face of the planet. And look at what has been produced under design–bid–build and low bid mentality! Imagine what we could do if we started to consider that full life benefit instead of our own vested interest and identities. It's such a different outcome and everybody would walk away feeling they had a wonderful experience.[20]

Notes

1 Kiel Moe, "Automation Takes Command: The Nonstandard, Unautomatic History of Standardization and Automation in Architecture," in Robert Corser (ed.), *Fabricating Architecture Selected Readings in Digital Design and Manufacturing*, New York, NY: Princeton Architectural Press, 2010, pp. 152–167, p. 164.

2 Barbara Jackson, Interview by authors, phone interview, Denver, CO, August 21, 2013.

3 E202–2008, or Building Information Modeling (BIM) Protocol Exhibit, provides terms of use of a BIM model, see B. J. Novitski, "AIA To Release New IPD and Design-Build Documents," *Architectural Record*, archrecord.construction.com/news/daily/archives/081002aia.asp, October 2, 2008.

4 AIA, AIA Minnesota, School of Architecture—University of Minnesota, “IPD Case Studies,” www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab093703.pdf (accessed March 18, 2014).

5 Ibid, p. 4.

6 AIA, “Integrated Project Delivery,” American Institute of Architects, http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab089099.pdf (accessed August 23, 2013).

7 C195–2008, or the *Standard Form Single Purpose Entity (SPE) Agreement for IPD.*

8 AIA, “IPD Case Studies,” p. 20.

9 Ibid.

10 American Institute of Architects, “2011 Integrated Project Delivery Awareness Survey,” Center for Integrated Practice.

11 AIA, “IPD Case Studies,” p. 20.

12 Ryan Smith, “PREFAB, BIM and IPD | BIM + Integrated Design,” BIM + Integrated Design | confronting the forces that create an immunity to change, http://bimandintegrateddesign.com/2011/03/27/prefab-bim-and-ipd/ (accessed August 9, 2013).

13 Albert Cheung, “Comment: It’s A Matter of Trust – The Architect’s Newspaper,” The Architect’s Newspaper, http://archpaper.com/news/articles.asp?id=4063 (accessed March 18, 2014).

14 Renee Cheng, AIA, Katy Dale, and Assoc. AIA, “The American Institute of Architects – Increase perceived design quality with collaborative delivery methods, Programs & Initiatives,” The American Institute of Architects – AIA Homepage, http://www.aia.org/about/initiatives/AIAB093906, April 2012 (accessed March 18, 2014).

15 AIA, “IPD Case Studies,” p. 19.

16 Barbara Jackson, Interview by authors, phone interview, Denver, CO, August 21, 2013.

17 Leigh L. Thompson, *Creative Conspiracy: The New Rules of Breakthrough Collaboration*, Boston, MA: Harvard Business Review Press, 2013, p. 15.

18 Ibid., pp. 12–13.

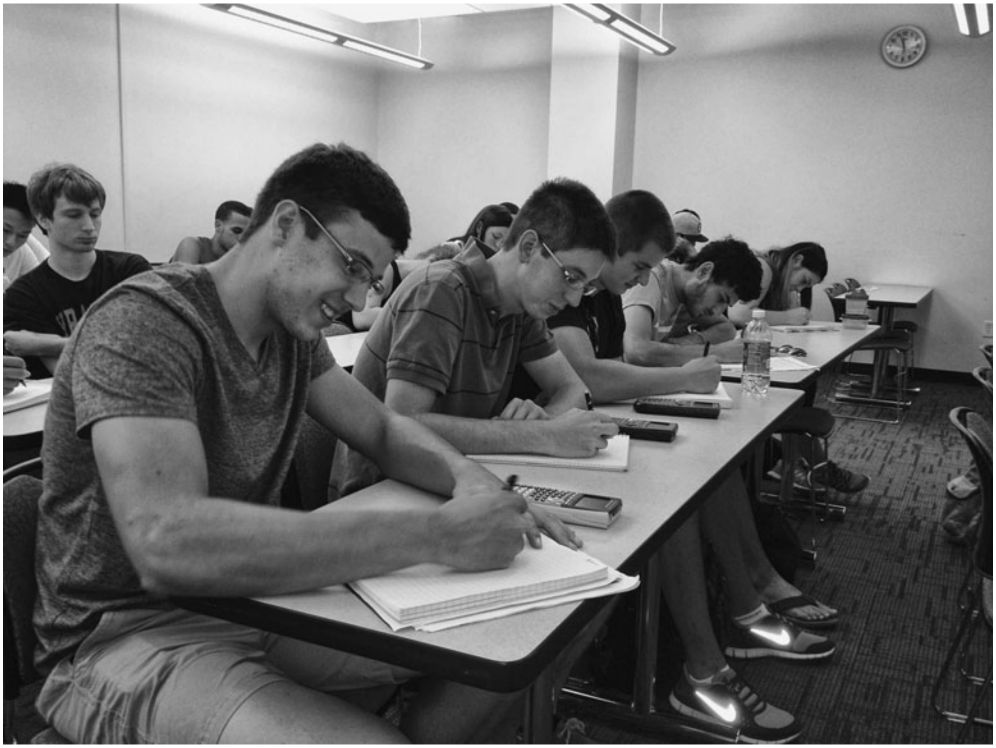
19 AIA, “IPD Case Studies,” p. 10.

20 Jackson, Interview.

– 15 –

Architecture and Engineering Pedagogy

ALTHOUGH architects and engineers alike are fundamentally engaged in design, the pedagogical methods employed in their training could not be more different. Open-ended problem-solving using multiple methodologies in pursuit of completing goals marks architectural teaching and contrasts with the deterministic, one-problem-at-a-time approach of many engineering courses. Even the physical space where the students work is different.



15.1 Engineering classroom.

© Sinéad Mac Namara.

15.2 Architecture studio.

© Clare Olsen.

While most engineers have little exposure to design and big picture thinking during their schooling, architecture students are not always expected to integrate complex technological building systems in their design proposals. These content differences between the disciplines are understandable given the diversities in practice; however, the methods of relaying content also have a profound effect on the different ways that architects and engineers approach work.

As discussed in Chapter 2, the division between architecture and structural engineering only emerged after the Industrial Revolution. Similarly, the educational experience in both disciplines has diverged over time. Initially, in both disciplines, training for the profession came in the form of apprenticeships rather than through university education. In the past century, the polar divide in the approach to educating architects and engineers has become quite pronounced in a large number of architecture and engineering programs across the US. In Europe, on the other hand, some architecture schools, particularly German and Swiss schools, have more significant mathematics requirements for entry and focus on more technical courses within the programs. It is argued that this contributes to European dominance in technologically innovative architecture.[1]

Despite the increasing reliance on architecture–engineering collaboration in the professional world, in the US, students from the disciplines generally have few opportunities to mingle. Although the National Architectural Accrediting Board (NAAB) encourages Interdisciplinary Collaborative Skills[2] and design teams are becoming more common,[3] engineering and architecture collaborations are not as widespread.[4] ABET, the analogous organization in engineering, similarly advocates for multidisciplinary learning, specifically in a team context. Departmental isolation in the modern university, however, puts many obstacles in the way of such collaborations. The emphasis on increasing specialization, overloaded curriculums, budgetary models that discourage cross-enrollment, and the fact that there are vastly different pedagogical approaches to teaching architecture and engineering all contribute to keep engineering and architecture students apart in their formative educational years.

> In engineering education today the problems are over constrained, but in architecture education I really believe that the problems are under constrained.[5]

This comment from John Ochsendorf, a Professor of both Architecture and Civil Engineering at MIT, encapsulates the fundamental dissonance between the two educational models and illuminates perhaps the biggest obstacle that the two groups have in working with one another at the academic level.

Architects and engineers interviewed for this book were asked how well the academies are preparing architecture and engineering graduates for collaborative practice. It is worth noting that most of those interviewed also teach, and thus are very well positioned to comment. A common answer came from architects and engineers alike, with the overwhelming majority responding "not very well." Faculty and institutions recognize the crucial need to address these pedagogical issues, especially in professional degree programs that are obliged to prepare students for the practice. Here, we identify some of the primary concerns that pervade contemporary architecture and engineering curricula with the goal of identifying opportunities to enhance student learning.

Open-ended versus Single Solution Problem-solving

The typical problem or assignment tackled in an engineering course will have a single answer (often found in the back of the textbook!) while the typical problem or assignment in an architecture course will ideally result in as many solutions as there are students in the class. One of the primary reasons for this difference is the types of problems assigned to engineering students. Inputs, dimensions, boundary conditions, and other specifications are given and the goal of the assignment is to solve (usually mathematically) for one or two unknown parameters. Because the problems are generally linear in nature, the methods used to solve them can be almost identical for each student. In an architecture design studio, on the other hand, course problems are more loosely and broadly defined, and there are multiple goals inherent in the problem. Students often have agency in how they approach the problem and there are numerous acceptable methods for providing solutions.

There are very good reasons why this is so. Engineering education is obligated to cover a high volume of technical material, focusing, for example, on codes, constraints and mathematical problem-solving. Engineering courses are both more like one another and more narrow in their focus, as befits the attempt to convey specialized knowledge. Eric Long of SOM, describes how the industry looks for technical competence when hiring graduates: "Engineering candidates need to be extremely technically sound. We usually only hire graduates with masters degrees that come from schools with solid technical classes and thesis work."[6] In contrast, architecture courses will often draw on disparate ideas and theories with the goal of preparing students for the breadth of experiences and design opportunities they may encounter in the working world. In architecture, there is necessarily more emphasis on the capacity to weave together multiple strands of information and ideas since there are generally multiple problems to address within a single assignment.

If one considers architecture and structural engineering, it is possible to make the broad generalization that the difference between engineering pedagogy and architecture pedagogy is one of depth versus breadth. Given their respective roles in design and construction, the differences in curricula are understandable; however, the strict adherence to these problem-solving methodologies during education can lead to difficulties in communication when working together in the professional realm.

Synthesis and Design

For engineering students in the US, the curricular emphasis on technical skills and bounded problems means that synthesis of those skills through a complex design problem usually comes late in the undergraduate student career. Increasingly engineering education researchers are concerned that so much time is spent on skill-building and knowledge-acquisition that there is little or no time in the curriculum for this vital synthesis. This approach assumes that they will "be able to develop a solution by combining them . . . eventually . . . the effort involved in learning about the small pieces is so overwhelming that we can no longer synthesize the original problem—the parts become more important than the whole."[7] Further, the engineering curricular focus on solving one problem at a time, assuming a singular answer or solution, stands in direct contrast to what noted historian of science Thomas Hughes calls "the history of modern technology and society in all its vital messy complexity."[8]

In most civil engineering programs throughout the US, there are few design opportunities for students. Most will have a freshman design course (often the only engineering course in a math- and science-filled curriculum) and a final capstone design course, which is required by ABET. ABET argues, "Students must be prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints."[9] The intervening years are described by engineering education researchers as "the valley of despair" in terms of design experience or exposure to engineering creativity.[10] The capstone course comes in the last semester or two of the program, consisting of about five to seven hours of work per week with three hours or less in contact with advisors.[11] The contact hours and number of occurrences in the curriculum demonstrate the marked differences in design education in architecture and engineering. Engineering education researchers argue that the stark differences between the highly defined problems encountered in the typical lecture or lab and the more complex, less defined, open-ended projects in the capstone course present a significant challenge to student success.[12] Similarly, students' relative lack of experience with finding appropriate design problems for capstone courses makes faculty mentorship and contact time extremely important.[13] For an experience that should act as a bridge to a more independent work life, this is an issue of concern. In fact, the lack of design skills stemming from a traditional engineering education has long been an issue of concern. Legendary engineering designer and collaborator Ove Arup is reported to have responded to a young engineer seeking a position by listing his impressive academic and technical expertise as follows: "I'm sure that's very important, but if you meet an architect, can you design things . . . can you design a structure?"[14]

Interviewees for this book had differing responses to this issue of design readiness. Hans Schober of SBP argued strongly that engineering students should undertake more design courses and specifically interdisciplinary courses with architecture students.[15] Rich Garlock of LERA (who also teaches engineers at Princeton) emphasized that engineers, like architects, need to be prepared to sketch ten ideas then throw away eight if they are to really take part in the design process.[16] Both Kurt Clandening[17] of John A. Martin and Guy Nordenson[18] similarly asserted that engineering graduates have to be broken of the habit of arriving at one workable solution for a problem, then refusing to pursue further alternatives.

Unlike engineering curricula, in architecture, design is the primary pedagogical focus. Architecture students continuously engage in creative thinking, keeping an eye on the big picture, while attempting to sort the aesthetic, functional, environmental, cultural and economic implications of their design proposals. In the professional realm, architects must reconcile numerous, sometimes competing goals for a project, making big-picture thinking a crucial part of everyday practice. Because of this, a range of methodologies for design is offered to students and they learn different techniques or combinations of techniques to approach similar problems. In these design-focused curricula, not all architecture students are taught the same depth of building systems expertise. The NAAB requires only two semesters of structures education, and most architecture students take few college-level mathematics and science classes. Of course, there are exceptions to this mode, and requirements vary across different programs and types of institutions. Architect and educator Neil Denari supports increased discussions about technical integration, saying, "It's very important to get the message across to the student that all the elements of building are part of a palate of tools that are instrumental to constructing a set of ideas and sensibilities . . . Structures, in particular should be taught as much poetically and conceptually as it is professionally." He further argues that architects need to be taught how to talk about architectural values and specific project design objectives with engineers.[19] This is essential because there are ever-increasing technical complexities at play in contemporary architecture and architects in training will grapple with these issues through collaboration once they've entered the professional realm.

There is no question of the fact that architects gain significant technical knowledge through working in the practice, and similarly, structural engineers who work closely with architects gain insight and skill in design. However, collaborations during their education represent a rich opportunity to better equip both groups to succeed in the working realm.

Exposure to Practice

In architecture schools students are exposed to the best examples of creative endeavor and cutting-edge design practice. Through history and theory courses, they learn how notable moments in history occurred when architects challenged norms, and how new styles, forms, and technologies evolved. By the same token, students in design courses often study precedents to learn about similar site conditions, program types, or technologies that they wish to display. Architecture students are thus very familiar with a wide canon of exemplary contemporary and historical projects. Most architecture faculty are actively engaged in design and making, and many schools have practicing architects who teach part time. Travel for the purposes of sketching, investigating, and analyzing existing works of architecture old and new is a fundamental aspect of architecture education. Site visits every semester and longer trips abroad for a semester or a year at a time are standard in most architecture programs. Lectures from notable practitioners or critics are an almost weekly feature in schools of architecture.

In contrast, in engineering programs, history courses are very rare, and exposure to contemporary practice is far less consistent than it is in architecture. Eric Long from SOM laments, “One thing engineering education lacks is exposure to history and precedent studies. It would be wonderful to study the bridges of Robert Maillart, for example.”[20] Although practicing engineers are often drafted in to help teach capstone design courses, most engineering academics engage in primary research rather than design. The authors found in surveying their own engineering students, for example, that second and third year students struggle to name engineers, buildings, or products of engineering that they admire—in fact they were more likely to have some favorite architects![21] It is difficult to imagine a medical student who could not name a disease that modern medicine had cured, or a music student without a favorite composer or performer, yet the engineering education system seems to leave students entirely divorced from the products of their profession. This surely hinders communication during future collaborations with architects.

Interdisciplinary courses, where each group must teach the other to some degree, represent an opportunity for engineering students to become more familiar with their intended profession and the design world more generally, and for architecture students to learn how to best communicate with those with technical expertise who may not initially share their interests or concerns in the larger design realm.

Visual Representation in Engineering Curricula

While well versed in the language of mathematics, and at a minimum competent in verbal and written communication, engineering students are often not formally or even informally trained in the other (and arguably most important) mode of communication in the design world: the visual, i.e. drawing, sketching, and modeling. Many engineering programs incorporate some CAD software instruction and some training in how to read plans and sections into a first-year introduction course and perhaps again in a capstone course, but visual representation is not formally part of the overwhelming majority of engineering curricula. It might surprise students to learn that practicing engineers interviewed replied with one voice to the questions "Do you draw? Is drawing an important tool for communication in your practice? Should engineering students be taught to draw?" "Yes, yes, and yes" was the almost universal response.

Drawing and other forms of visual representation are important for developing spatial reasoning and the capacity to visualize the un-built in three dimensions. It is also a tool for developing one's own design concepts and communicating those concepts to colleagues and interdisciplinary collaborators. Garlock observes that drawing is fundamental to the development of design ideas for engineers and laments that not enough engineering students develop their freehand drawing skills.[22] Schober reports that he often makes a rough 3D model in Rhino, which he can then print and sketch over to help him conceptualize a new problem.[23] Nordenson (who also teaches structures to architecture students at Princeton) notes that the engineers at his firm use drawing *and* models to investigate and communicate design ideas among themselves and with their architecture collaborators.[24] Xavier De Kestelier reports that when Foster + Partners incorporated in-house engineers, they were quick to adopt the 3D printer and the laser cutter as tools for communication and design.[25] Thus, it is clear that in the professions the tools of visual representation *are* important to both in-house and collaborative practice, and that many engineers learn the value of those tools on the job. Interdisciplinary courses can begin this process and better prepare engineering students for effective communication with their architecture collaborators. This concern for the engineer's capacity to engage in visual culture as a way to better engage in design is not new. Writing in 1959 about the obstacles to collaboration between architects and engineers, Ove Arup declared, "The Author believes firmly that the civil engineers should learn more solid geometry, freehand sketching, and appreciation of architecture."[26]

Technical Rigor in Architectural Curricula

If one looks at the work of many prominent historical figures in architecture such as Antoni Gaudí, Louis Kahn, and Buckminster Fuller in particular, it is clear that architects of the modern period were well versed in mathematics and structural principles. However, if engineering students are deficient in exposure to practice and visual culture, architecture students are often critiqued as lacking in technical rigor.

One defense of the perceived lack of technical depth in architecture education is that there is simply too much material to learn it all comprehensively, and further that some technical knowledge is best gained through practice. Architect Toshihiro Oki claims that it is only when "you see the reality of working in the field that you wake up and figure out how to work with consultants,"[27] positing that through practice, architecture graduates will have either the need or the motivation to fully engage detailed technical requirements.

A complicating factor here is that although architecture students do take technical courses (certainly more than engineers do design courses) there is good evidence to suggest that students do not absorb this knowledge (or indeed many other types of knowledge) when it is presented in lecture format without a design context. John Folan, professor at Carnegie Melon, asserts:

> Delivered outside the context of a design scenario, already abstract concepts of social, legal, economic, and contractual performance become entirely opaque, or even impenetrable for most students. As a result, the content remains entirely irrelevant in the academic setting and many students emerge into the profession without capacity to evaluate priorities as they relate to performance.[28]

This observation is supported by education research that demonstrates the value of "just in time" learning where students learn complex tools and skills (a specific math concept for example) best when they have immediate need of that tool to achieve some other immediate work goal.

When the teaching of technical material is relegated to lectures and not emphasized in studio culture, or when rigorous technical standards are seen only as barriers to creative design, it is a missed opportunity. This aspect of architectural education culture present at many (but by no means all) schools can lead to naiveté on the part of architecture students as to what technical knowledge they themselves might reasonably claim and the degree to which real design work is a collaborative practice that requires interaction with other experts. This is the single most important thing about technical education for architects. It is imperative that architects are taught to work well with engineering experts of all kinds, so that they can maximize the design potential of emerging technologies, and where better to start than with the engineering students on their own campuses?

Summarizing the Critiques

This critical look at architecture and engineering pedagogies points to gaps in the professional preparedness of students. Greg Otto of Buro Happold, trained as both an architect and an engineer, offers this summary of the failings of traditional educations of both disciplines:

> My personal comment is both architecture and engineering educational systems are failing the market. Neither is training people in the way that the industry or market requires. Engineering graduates are too "silo-ed"—they can design beams and columns but they can't think big picture and certainly don't understand

> business well. Architecture graduates are too caught up in the novel and sensational, and sometimes in doing the digital for the digital's sake. Architecture has lost sight of how to build. Engineers are coming out with a lot of theory, architects with a lot of design. But nobody is coming out with how to make buildings. It's a complete vacuum. You can see it in engineering companies these days that are running away from risk.[29]

As architectural and engineering education research has acknowledged for years, and our interviewees who are practicing at the highest level agree, curricula in both disciplines must dramatically evolve to reflect the growing complexity and multiplicity of contemporary practice. Interdisciplinary collaborations offer an opportunity to better prepare students for the working world. The next section describes the potential of these kinds of courses, highlighting a few examples of positive learning outcomes through academic case studies.

Future Directions: Creative Learning through Collaboration

As has already been described, cutting-edge architectural practices are becoming increasingly collaborative at early stages of design. In a paper discussing a design studio generously funded by the University of Michigan that combined students and faculty from Art & Design, Materials Science & Engineering and Architecture, Marshall, Shtein and Daubmann explain:

> As these new models of practice manifest, new pedagogies also become necessary, often challenging both existing educational models and institutional constraints as a result . . . For educators a central question arises: How do we prepare students to be extra-disciplinary thinkers and doers with “habits of mind”[30] that prepare them to make the sort of hybrid responses that complex performance problems demand?[31]

Interdisciplinary courses have the potential to prepare students for meaningful cross-disciplinary design collaborations in the working world and can prove to be pivotal in students' educational careers.

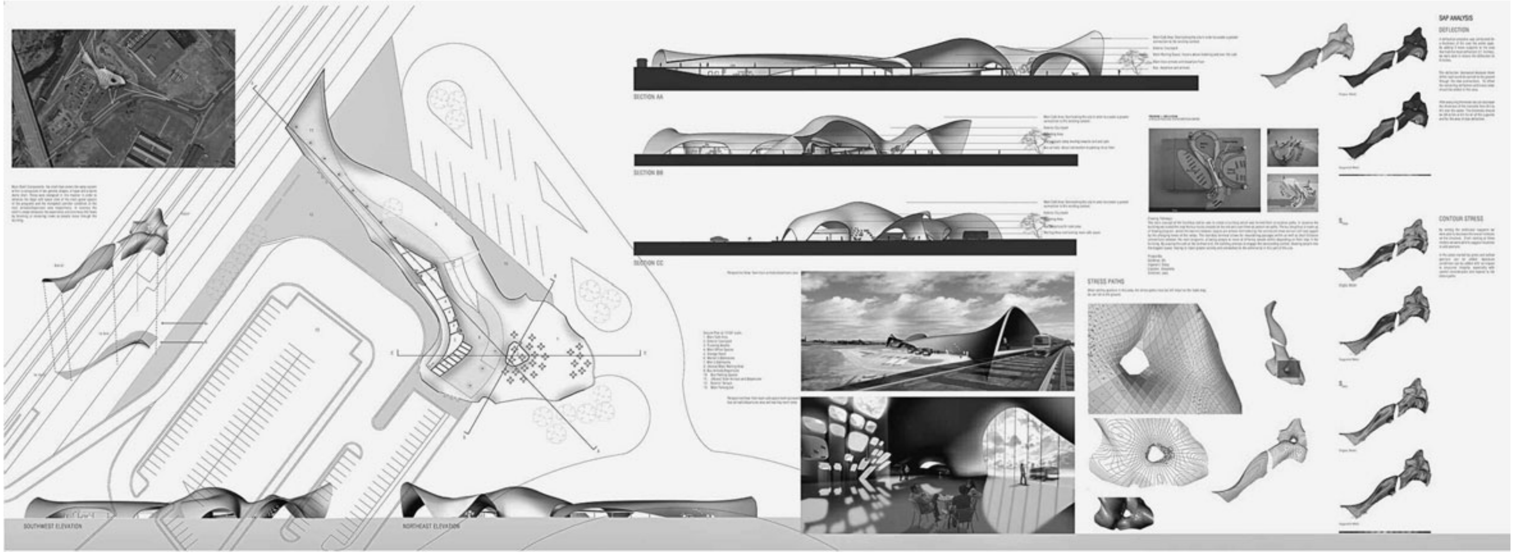
Given the richness of the interdisciplinary experience, it is hopeful that an increasing number of schools will offer interdisciplinary courses in the future.[32] The following section describes the lessons learned from three cross-disciplinary courses.

Syracuse University Architecture and Engineering Collaboration: Shell Structures

Recognizing the potential benefits for interdisciplinary course work for professional programs to integrate creativity in engineering education, encourage architecture students to strive for greater technical resolution, and to align pedagogy with practice, the authors, with support of the Deans of the Schools of Engineering and Architecture, secured a National Science Foundation Engineering Education grant. One of the priorities under the grant was to develop a transdisciplinary design studio (TDS), which was co-taught by the authors in two iterations to a mixed group of architecture and engineering students.

The topic for the course was Shell Structures, chosen because shells represent a pure integration of structure and form—the two are inseparable and must be considered simultaneously to achieve material efficiency and experiential dynamism. We also found that it was a relatively new topic for all the students involved, which allowed for a common starting ground for the learning process. We approached lectures on this topic from the perspective of our respective fields. We discussed historical and contemporary precedents, provided technical tutorials (on structural efficiencies, materiality and math) and software instruction. There were also a number of sessions devoted to design charrettes and reviews. The faculty attempted to integrate creative and research activities such as open-ended problem-solving, resolving competing goals in a complex problem, balancing technical merit against architectural design values, and positing speculative designs. The students undertook a series of design assignments that had both engineering and architecture goals in integrated groups. In order to test and represent ideas, students were encouraged to work together in the development of Rhino models, analyzed in SAP 2000, and visualized through hand-made and digitally fabricated models.

Among the primary observations by the education evaluation team of this course was high enthusiasm and high adaptability on the parts of engineering and architecture students for interdisciplinary learning. The evaluation team was surprised to note that they could not always distinguish engineering students from architecture students in the final reviews. They also observed a high degree of "buy-in" by the students to both the course itself and the evaluation process, reporting that students were enthusiastic about this new and different opportunity and anxious to do their part in making it a permanent part of the curriculum. The faculty observed the importance of mutual discussions about disciplinary specific vocabulary and design goals among students from both disciplines to ensure positive outcomes in the design assignment.



15.3 Syracuse University Shell Structures course student collaborative final presentation board for a Regional Transportation Center in Syracuse, NY.

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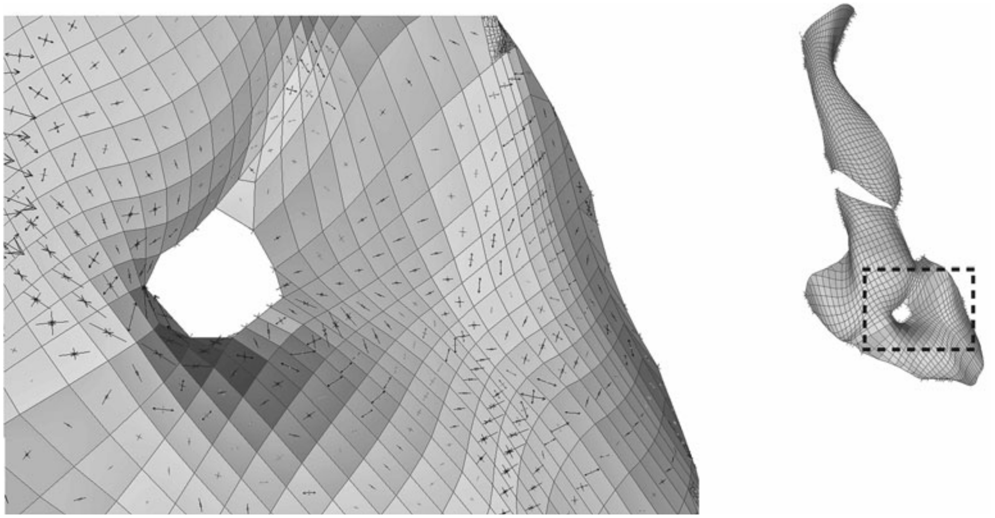

15.4 Syracuse University Shell Structures course student collaborative final project showing SAP 2000 stress path analysis.

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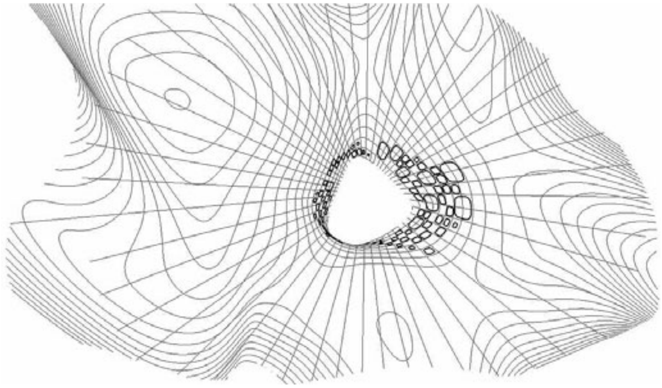

15.5 Syracuse University Shell Structures course student collaborative final project showing stress path analysis for aperture placement.

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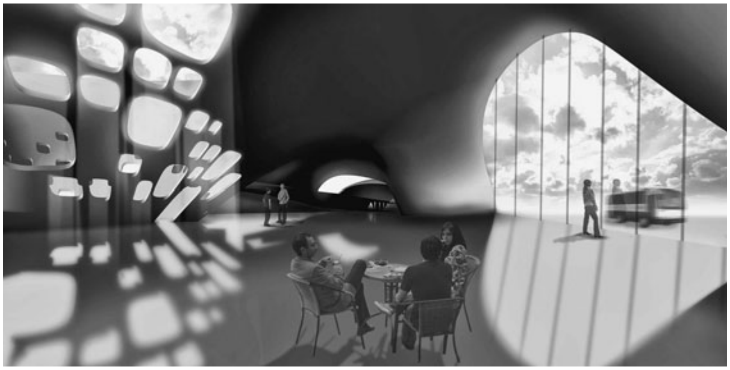


15.6 Syracuse University Shell Structures course student collaborative final project interior rendering for a Regional Transportation Center.

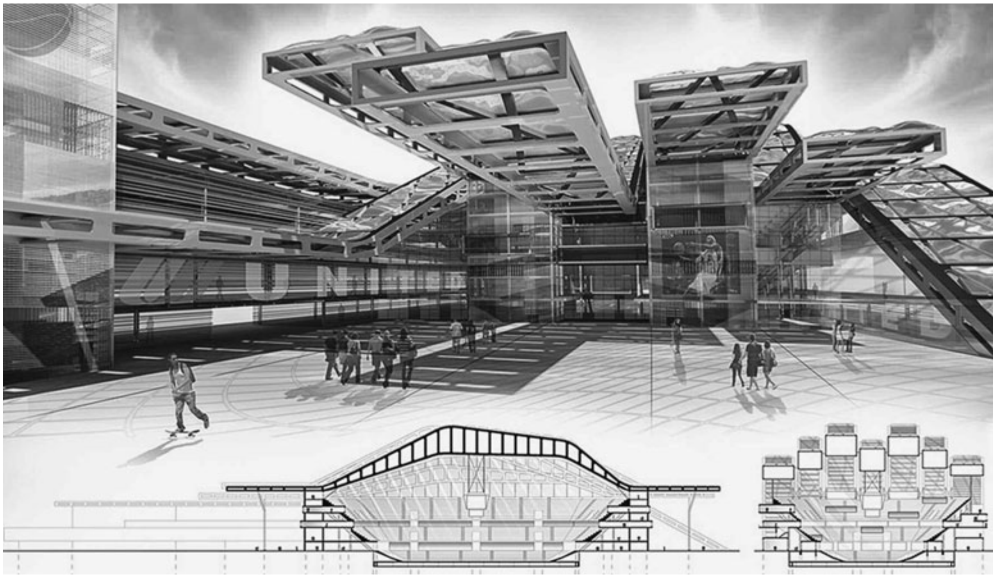
© Goldman, Ingersoll, Lipezker, and Solomon.

Cal Poly Architecture and Architectural Engineering Studio: A Collaboratory

At California Polytechnic State University, San Luis Obispo (Cal Poly), Architectural Engineering (Arch-E) professor Kevin Dong spearheaded an interdisciplinary collaboration, which started as an off-campus collaboration[33] in its first year, and in subsequent iterations over eight years, involved a partnership with Cal Poly's Department of Architecture and faculty members Jim Doerfler, Thomas Fowler and for a time, Mark Cabrinha. Since the faculty were teaching the interdisciplinary courses for architecture and architectural engineering students as an overload, it was helpful to have multiple colleagues involved to share the time commitment. Additionally, the faculty forged strategic academic and industry partnerships with ARUP (Dong's employer before he began teaching) who gave workshops on collaboration and provided feedback during a weekend-long charrette, and education specialists at AutoDesk who supported the digital learning process.

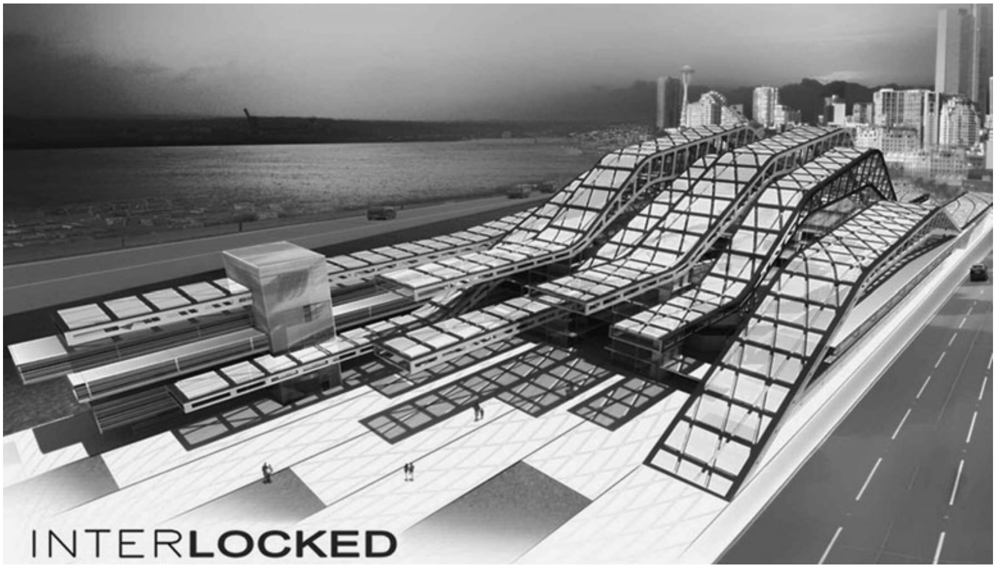
In each iteration, undergraduate students from both disciplines who were completing their fourth year (with the addition of a few graduate students) were joined for a two-quarter studio to design buildings with either a long span or tall building component. For the Arch-E students the studio served as the senior project and for the architecture students, it was an elective studio.[34] The studio met on Tuesdays, Thursdays and Saturdays (to accommodate the faculties' schedules since they teach other studios on Mondays, Wednesdays and Fridays) and as a result, the teaching approach was a little less formal, which helped to support the collaborative process, which was a bit slower.[35] The faculty began each quarter with a team-building exercise, and then the students co-developed the conceptual framework that drove project development. The students were asked to do a lot of physical modeling, and to learn digital tools, which helped to establish a common ground. They bonded through field trips (to visit the project site, significant nearby buildings, and architecture and engineering offices in that city) and ultimately developed highly integrated architecture, structural and cladding systems that were presented by the students to faculty and practitioner juries. Students received lectures from faculty and practitioners on structural/cladding systems, siting, massing, adjacency, materiality, programming, natural ventilation, day lighting, computer generation and modeling, and constructability. A high degree of ownership was fostered in all team members from day one of the project: "handing off" (where the architects might make the form and then the engineers resolve the structure) was forbidden. All students worked together at the same table for the duration.[36] At least once during the courses, students from each discipline were asked to present the concerns and challenges of the other discipline; in other words, the architecture students presented the structure and the engineering students presented the architectural aspects.

Faculty cite numerous benefits that resulted from pairing students in architecture and architectural engineering. "The most telling comment about the success of the studio is when someone from the jury asks 'which one of you is an architect and which one of you is an engineer', after the presentation has finished."[37] Faculty also describe observing valuable "negotiation and collaborative decision-making skills" and that the course enabled faculty to



15.7 Cal Poly State University Collaboratory final project for a Sports Arena Complex in Seattle, WA.

© Dong, Nevius, Shorey, Tomitch, Towers.



15.8 Cal Poly State University Collaboratory final project for a Sports Arena Complex in Seattle, WA.

© Dong, Nevius, Shorey, Tomitch, Towers.

"contextualize the education that students are getting in the classroom and better prepare students for the range of practice models they will be exposed to after graduation."[38] The courses have been recognized at multiple academic conferences,[39] receiving a national NCARB Prize in 2010 for demonstrating "Creative Integration of Practice and Education in the Academy."

University of Washington Architecture and Construction Management Collaboration: Integrated Project Delivery

Kathrina Simonen, Carrie Sturts Dossik and Robert Peña collaborated at the University of Washington to offer an integrated studio for students of architecture and construction management. The course was developed in 2008 and has since been offered as a capstone project for students who are dual majors in both subjects and as an optional studio for students majoring in either discipline. The course was modeled on practice in the industry with faculty acting as principals who give direction, identify when outside technical help is required, and facilitate team and individual meetings as necessary.[40]

Students from both disciplines worked in teams and used an Integrated Project Delivery (IPD) model (see Chapter 14) to generate and deliver design proposals. Student teams received design feedback along the way from professionals in the design and construction industries. The students used BIM tools (see Chapter 13) and applied skills learned in previous courses to develop their designs that integrate aesthetic goals with performance criteria as measured by a conceptual cost estimate, a construction plan, and a schedule. The designs were required

15.9 University of Washington Arch/CM 404 Winter 2013 student group design of a modular high rise, final rendering.

© Hovhannisyan, Lei, Leigh, Sistek, Tritt and Wienker.

to consider alternatives for massing, structure, and enclosure systems, and to achieve high performance and sustainable building criteria.[41]

Faculty found that it was imperative to require the construction management team to evaluate multiple options early in the design process to generate more informed decisions about architectural options, and to foster an appreciation of the iterative nature of the design process. Without this formal requirement of iteration, the construction management students, who are used to a linear process with a well-defined problem, often become frustrated when the designs change and wait until the design is well formed to complete their analyses, defeating the purpose of early collaboration.[42] In teaching, refining, and evaluating the class, the faculty also observed the importance of team dynamics to project success. They argue that it was important to understand that different teams develop different working dynamics, and that it is imperative to have at least two strong leaders in a group. A further observation was that although they were initially reluctant to do so, taking part in early conceptual design conversations was critical for the non-architecture students, since it formed the basis of integrating them successfully into the design process.[43]

Conclusion

As these few examples demonstrate, interdisciplinary courses are challenging, but offer numerous rewards. Complex collaborative design work that encompasses technical, social, economic and aesthetic goals is vital to prepare graduating architects and engineers for the challenges they will face in a world with crumbling infrastructure, rapid development in emerging economies, resource scarcity, and climate change. For schools that strive to impart creativity and technical skills to produce innovative design proposals, interdisciplinary collaborations have the potential to instill confidence in the aesthetic project while emphasizing integrated systems and material efficiency in the pursuit of sustainable design. The Appendix offers guidelines for faculty and administrators developing interdisciplinary courses.

Perhaps the future of interdisciplinary education will look more like that of the past. The Werkbund at the Bauhaus, which started in Germany in 1919, was initially developed with the intent of increasing industry competitiveness. The initial premise of the school grew out of similar ideological challenges that mark discussions today—how can architecture and engineering pedagogy reflect and influence contemporary practice and industry? As Bergdoll describes in the foreword to the 2009 Bauhaus exhibition catalogue:

> In challenging the way traditional academies taught students through the imitation of historical models, the Bauhaus worked as a laboratory for ongoing experiment. In his 1919 program for the Bauhaus, Gropius wrote that the arts had become "isolated" in the modern age and the school had to forge a "new unity" . . . Such crossing of the boundaries gets to the heart of what we feel is central to the Bauhaus's legacy today.[44]

Perhaps academically focused linkages with industry will become more the norm and will further expand upon pre-professional goals in curricula. Through cross-disciplinary and industry partnerships, students will learn there is tremendous potential in collaborative design to pursue forward-thinking projects with real-world applicability.[45]

Notes

1 Peter Buchanan, "Why is Europe Winning?," *Architect*, 94 (2005): 17–18.

2 NAAB: Integrated Practice Skills and Knowledge Teaming: 7b. Interdisciplinary Collaborative Skills – Ability to work on interdisciplinary design teams in collaboration with other disciplines to successfully complete integrated design projects.

3 Robert Smith, "2009 and Beyond: Revisiting the Report on Integrated Practice: Suggestions for an Integrative Education." http://www.aia.org/about/initiatives/AIAB082222 (accessed March 18, 2014). Smith paraphrases Renee Cheng in her comment that "more and more students all across the country are working on design projects in teams – which has been a big change in the past few years."

4 In a survey of architecture programs (cited in Table 2, p. 43 of the following article), 4 out of 54 had some form of interdisciplinary coursework. B. De La Harpe, J. F. Peterson, N. Frankham, R. Zehner, D. Neale, E. Musgrave and R. McDermott, "Assessment Focus in Studio: What is Most Prominent in Architecture, Art and Design?," *International Journal of Art & Design Education*, 28 (2009): 37–51. doi: 10.1111/j.1476-8070.2009.01591.x.

5 John Ochsendorf, "Teaching Architectonics," Keynote lecture, Building Technology Educator's Society Conference, Bristol, RI, July 11–13, 2013.

6 Eric Long, Interview by authors, phone interview, San Francisco, CA, August 2, 2013.

7 L. Katehi, "The Global Engineer," *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, National Academy of Sciences, 2005, p. 4.

8 T. P. Hughes, *American Genesis: A History of the American Genius for Invention*, 1st edn., New York: Penguin Books, 1990, p. 5.

9 ABET Criteria for Accrediting Engineering Programs, 2010–2011, Criterion 5: Curriculum, p. 4.

10 D. Kotys-Schwartz, D. Knight, and Pawlas, G., "First Year and Capstone Design Projects: Is the Bookend Approach Effective for Skill Gain?," *Proceedings of the American Society for Engineering Education 2010 Annual Conference and Exposition*, June 2010, Louisville, KY.

11 R. H. Todd, S. P. Magleby, C. D. Sorensen, B. R. Swan, and D. K. Anthony, "A Survey of Capstone Engineering Courses in North America," *Journal of Engineering Education*, 84(2) (1995): 165–174.

12 J. Palmer and H. Hegab, "Developing an Open Ended Junior Level Laboratory Experience to Prepare Students for Capstone Design," *Proceedings of the American Society for Engineering Education 2010 Annual Conference and Exposition*, June 2010, Louisville, KY.

13 W. Leonard, R. Merril, and E. Dell, "An Innovative Method Providing and Alternative to Capstone Courses Using Experiential Learning," *Proceedings of the American Society for Engineering Education 2010 Annual Conference and Exposition*, June 2010, Louisville, KY.

14 Derek Sugden, Foreword to *Ove Arup Philosophy of Design: Essays 1942–1981*, ed. Nigel Tonks, London: Prestel, 2012, p. 6.

15 Hans Schober, Interview by authors, phone interview, Stuttgart, Germany, June 19, 2013.

16 Richard Garlock, Interview by authors, phone interview, Princeton, NJ, June 25, 2013.

17 Kurt Clandening, Interview by authors, phone interview, Los Angeles, CA, May 24, 2013.

18 Guy Nordenson, Interview by authors, phone interview, New York, NY, June 14, 2013.

19 Neil Denari, Interview by authors, phone interview, Los Angeles, CA, June 25, 2013.

20 Eric Long, Interview by authors, phone interview, San Francisco, CA, April 23, 2013.

21 Sinéad Mac Namara, C. J. Olsen, Scott L. Shablak, and Carolina B. Harris, "Merging Engineering and Architectural Pedagogy – A Trans-disciplinary Opportunity?," *Proceedings of the 2010 ICEE Conference on Engineering Education*, Silesian University of Technology, Gliwice, Poland, July 18–22, 2010.

22 Garlock, Interview.

23 Schober, Interview.

24 Nordenson, Interview.

25 Xavier De Kestelier, Interview by authors, phone interview, London, UK, May 25, 2013.

26 Ove Arup, "The Architect and the Engineer," *ICE Proceedings*, 13(4) (1959).

27 Toshihiro Oki, Interview by authors, phone interview, New York, NY, July 30, 2013.

28 John Folan, "Exclusively Mutual," *Performative Practices: Architecture and Engineering in the 21st Century*, ed. William Braham and Kiel Moe, ACSA Teachers Seminar, New York City, June 16–18, 2011.

29 Greg Otto, Interview by authors, in-person interview, Los Angeles, CA, June 10, 2013.

30 Mary Taylor Huber and Pat Hutchings, *Integrative Learning: Mapping the Terrain*, Washington, DC: Association of American Colleges and Universities, 2004, p. 1. Quoted in J. Marshall, M. Shtein, and K. Daubmann, "Smart Surfaces: a Multidisciplinary, Hands-on, Think-tank," *Performative Practices: Architecture and Engineering in the 21st Century*, ed. William Braham and Kiel Moe, ACSA Teachers Seminar, New York City, June 16–18, 2011.

31 Marshall, Shtein, and Daubmann, "Smart Surfaces."

32 See Note 4 above.

33 In the first year, Prof. Dong partnered his students with Thomas Leslie's students at Iowa State University. Although this partnership mimics what often happens in industry where colleagues aren't always co-located, Dong found that the local partnership enabled students to take their projects further and to learn valuable skills from one another about communication and presentation. Kevin Dong, Interview by authors, in-person interview, July 9, 2013.

34 Incidentally, the course is more popular among the architecture students.

35 Thomas Fowler, Interview by authors, in-person interview, May 7, 2013.

36 Thomas Fowler and Jim Doerfler, Interview by authors, email interview, August 30, 2013.

37 K. Dong, J. Doerfler and T. Fowler, "Interdisciplinary Design Studio—Identifying Collaboration," in *Proceedings of the Building Technology Educator's Society Conference*, Bristol, RI, July 11–13, 2013.

38 Thomas Fowler, quoted in National Council of Architecture Accreditation Boards, "The NCARB Prize 9 for Creative Integration of Practice and Education in the Academy," Washington, DC, 2010.

39 See for example, J. Doerfler and K. Dong, "The Interdisciplinary Design Studio—Understanding Collaboration," *Proceedings of the 2010 International Conference Structures and Architecture*, Guimaraes, Portugal and the proceedings of ConnectEd 2010 International Conference on Design Education, Sydney, Australia.

40 Kathrina Simonen, Carrie Sturts Dossick, and Robert Peña, "Reaching for Sustainability Using Technology and Teamwork: Testing Integrated Project Delivery in Multi-Disciplinary Studio Teaching," in *Proceedings of the American Society of Collegiate Schools of Architecture Annual Conference, 2011*, Boston, MA, March 2011.

41 Kathrina Simonen and Carrie Sturts Dossick, "Iteration for Integration: Techniques for Integrating Building Technology and Design," in *Proceedings of the Building Technology Educator's Society Conference*, Bristol, RI, July 11–13, 2013.

42 Ibid.

43 Simonen, Dossick, and Peña, "Reaching for Sustainabilty."

44 Barry Bergdoll, *Bauhaus 1919–1933: Workshops for Modernity*, Museum of Modern Art, 2009, p. 13.

45 A portion of this concluding text was included in C. J. Olsen and S. C. Mac Namara, *In Support of Pre-Professional Relations: Guidelines for Effective Educational Collaborations Between Architecture and Engineering*, ACSA 100th conference, 2012.

– Appendix –

Guidelines for Developing Interdisciplinary Courses[1]

The following guidelines are based on the Shells Structures course, co-taught by the authors at Syracuse University in two iterations. The faculty worked with Syracuse University education evaluators, Scott L. Shablak and Carolina B. Harris, who conducted focus groups and surveys at the beginning, middle and end of the two courses.[2] The education evaluation reports have enabled us to develop the following guidelines for future engineering and architecture collaborative courses.

Logistics/Course Structure

1. Interdisciplinary design can be taught at any point in the curriculum to either the same level of students or a mix of levels.

In our experience where both classes were composed of engineers from the third year and architecture students from a wide range of years, we found no clear indicators that interdisciplinary design should be taught at a particular moment in the curriculum. Although intuitively, it may seem that communication would improve among students who are at about the same level, at least in the Syracuse University context, the dominant personalities were not necessarily those in the higher age group.

2. The course structure works well as a hybrid of the design studio, seminar and technical lecture models, but because of time, should (ideally) run as a studio.

Lectures, lab instruction (on software or other technical topics) and group critiques enable general knowledge to be dispersed about vocabulary, history, precedents for the work, and technical skills. The group critiques are also an essential part of the design course so that students can understand the range of possibilities and learn from one another. At the same time, small group critiques, desk critiques and working sessions allow the instructors to give individual attention to groups and observe group dynamics more closely, which also facilitates intervention if there are communication issues in the group.

3. Instructors from each of the disciplines should (ideally) be present in the classroom together as much as possible.

Given tight budgets, this may be difficult to achieve; however, key learning (on the part of the students and instructors) occurs when multiple perspectives are voiced in the classroom. In order to address communication dynamics among students, it is helpful to understand their perspective, and the instructor's understanding can be gained, in large part, from observing and talking to the other instructor.

4. Invite outside experts—equally—from both disciplines.

Emphasize that each discipline is complex and that feedback from colleagues is an essential part of the design and learning processes. We would usually invite outside critics to review the work (as presented by the students), but we found that some engineering colleagues were unaccustomed to the review process and did not always provide constructive feedback, especially regarding technical concerns. It may be helpful to invite colleagues who have some experience with design teaching or even interdisciplinary collaboration.

5. Meet in a classroom that's not in the architecture school/department.

The Shells Structures courses met in the architecture school both years, and we now recognize (through the course evaluations) that the context alone provides comfort and sets a tone. Our goal was to emphasize creative thinking for the engineers, which naturally took them out of their mental comfort zone. Confidence-building and emotional comfort may result from teaching the engineers on their "home turf."

6. A note to department heads: Flexibility and support are hugely appreciated.

We were lucky enough to have the support of NSF and the two Deans, and this made logistical processes fast and relatively painless. Without administrative support, potential stumbling blocks may include obtaining numbers for cross-listing the course, determining the room, and deciding how to share equipment and material resources. Fingers crossed that your administration is as visionary as you are.

Content

1. Choose a topic that is relatively new to the curriculum of both disciplines.

As described in Chapter 15, Shells Structures turned out to be a well-suited topic for the Syracuse University curricula because it was new for both the engineering and architecture students. Although it is important to recognize and harness varying types of expertise among the students, it is also helpful to achieve a level playing field—a sensibility that everyone is "in it together." When growth is happening in parallel among a diverse group of students, they tend to forge bonds and help one another through the process.

2. In a 15-week semester scenario, we recommend no more than three short assignments (without a high degree of resolution) and a final project of about six weeks, which is more resolved.

In the case of the Shells collaboration, which emphasized open-ended problem-solving and creativity, we introduced a series of short projects so that there would be multiple opportunities for collaborating with different partners. We attempted to isolate the key design elements for the group to tackle, acknowledging very clearly what was being left out to avoid misconceptions about the design process.[3] On the positive side, we observed that the short assignments were helpful in building confidence through multiple attempts. However, student surveys revealed that the students were frustrated by the lack of time to delve deeply into design (especially later in the semester when we had allotted four weeks for the final project).

Tips for Teaching

1. Allow working sessions during class time in order to observe group dynamics and tactfully intervene when necessary.

As faculty already know, the complex craft of teaching involves nuances that change from student to student. In our experience, teaching an interdisciplinary course requires even more close observation and attention to psychology than other non-collaborative courses. Observing group dynamics during working sessions is an important evaluative tool to assess communication and learning.

Notes

1 These guidelines were first featured in the following paper: C. J. Olsen and S. C. Mac Namara, “In Support of Pre-Professional Relations: Guidelines for Effective Educational Collaborations Between Architecture and Engineering,” ACSA 100th conference, 2012.

2 For further discussion, see: S. C. Mac Namara, C. J. Olsen, Scott L. Shablak, and Carolina B. Harris, “Merging Engineering and Architectural Pedagogy – A Trans-disciplinary Opportunity?,” 2010 ICEE Conference on Engineering Education, Silesian University of Technology, Gliwice, Poland, July 18–22, 2010.

3 For example, in the first assignment in Shell Structures, we asked for five connected shells with specific square footages, but the site and program (type of function or activity of the space) were abstract and materiality was ambiguous.

– INDEX –