Realizing Architecture's Disruptive Potential

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In 1985, the world's best human chess player of the time, Garry Kasparov, simultaneously played against 32 computers. He comprehensively beat all of them. In 1996, he narrowly beat the world's most advanced chess-playing computer. In 1997 he was comprehensively beaten by the same machine. In 2016, a computer repeated the feat in the more difficult and ancient game of Go. *In 2012, as a fitting tribute to Artificial Intelligence pioneer, Alan Turing, the London Symphony Orchestra played music that was composed entirely by a machine,* Iamus. *The composition was widely applauded for its expressiveness and sufficiently intrigued human musicians.*

Digital technologies—computers and computer-controlled machines—have pervaded all aspects of life, delivering sustained and accelerated rates of societal and economic evolution. Yet, in architecture, such an embrace of digital technologies and attendant intellectual disposition is not widely accepted.[1] Whilst increasing numbers of progressive firms and research institutions are forging rapidly forward in such a technological upgrade, the larger populace of architects and the architecture produced thereof is decidedly averse to it. This unfortunate and hopefully temporary resistance notwithstanding, digital technologies will incontrovertibly be one of the key drivers of Innovation of our discipline and consequently the built environment in the twenty-first century.

Artificial Intelligence and Intelligence Augmentation

Closer inspection of the previous examples of machines bettering humans at innately human tasks, reveals some nuances. Post the cataclysmic event in 1997, the quality of human chess players worldwide improved dramatically by incorporating software in their training.[2] Additionally and interestingly, human-machine combinations routinely outperform supercomputers and superhumans. This can also be observed in the more recent development of Go players, robotic musicians accompanying human musicians,[3] in rescue operations post-natural disasters,[4] etc. Computers and robots are, contrary to popular belief, making humans better. Rapidly better. This lends credence to the underrated but seminal hypothesis of human-machine symbiosis by Licklider:[5] in the long-term future it seems entirely plausible that an artificial intelligence will dominate and, more pragmatically, in the near future there is an exhilaratingly-rich period of symbiotic progress to be worked and capitalized on. In other words, we are in the *Intelligence Augmentation* phase of human evolution. Architecture should not, and cannot, afford to be marginal to this. This article will, outline the two critical endeavors to exploit this innovation potential—a framework of architectural knowledge and collaborative design practice. The article will also illustrate the same with exemplar projects from Zaha Hadid Architects.

Architectural Knowledge

What could be the nature of an architectural knowledge that provides the foundations for architectural production in the digital age? Inspecting the concerns of such a knowledge base, one would discern two major divisions:[6] one aspect concerning itself with the *Technologies of Design and Construction* and the other with the *Conception of Design*. The former concerns itself with operational knowledge of computers and machines, material behaviors, structural systems, use of specific software, programming, etc. The latter includes knowledge related to spatial organization, styles of design, socio-cultural implications, and theoretical schools of thought. Witt poetically traces back such divisions, at least back to the famously contrary positions of the two protagonists of the Italian renaissance—Filippo Brunelleschi and Leon Batista Alberti. He suggests, implicitly inclined towards Brunelleschi that the current digital age could learn substantially from nineteenth-century efforts in systemic generation of architectural knowledge of the first kind—abstraction of mathematical knowledge into drawing instruments for specific types of complex geometry, manuals of construction for their physical realization. Schumacher, inclined towards Alberti's efforts, argues for a similar effort in incorporation of computational tools and scientific methods in the conception of design as well—specifically in the study of human perception of spatial features and the subsequent production of architectural meaning.[7] In others words, a computational understanding of *semiosis* that can then be used to *generate* spatial constructs that enhance such a process. This in turn helps humans to navigate the spaces harmoniously, complement and augment human activity within the space. Thus a fundamental necessity for sustained innovation is the development of a computational basis for both aspects of architectural knowledge—*Technological and Conceptual*—and further, their unification into a framework. There have been several, episodic and partial attempts at such frameworks: mathematician-turned-architectural-scientist Lionel March set up an architectural science research laboratory in Cambridge in the 1970s[8] and produced several influential publications including *Architecture of Form.*[9] His colleague Christopher Alexander made several seminal and influential contributions with his writings, especially his dissertation—*Notes on Synthesis of Form.*[10] Nicholas Negroponte set-up the Architecture Machine Group at MIT, also in 1970s. The necessity now is for unhindered, devoted pursuit and expansion of the same. This is imperative for architecture to be able to deliver similar accelerated rates of evolution as some of the other aspects of human evolution previously mentioned.

Collaborative and Co-Authored Design

The nature of relationship between architects, engineers, and contractor-builders in post-Renaissance history, has fluidly oscillated between being unified to being distinct and domain specialised[11] These role changes between architects and engineers are fascinating. Initially the two professions were indistinguishable on the basis of skill, but more by building task—civil buildings by architects, bridges by engineers for example. By the twentieth century, the roles had emerged to account for division of labour on the same building project—architect Sauvestre inflecting engineer Gustave Eiffel's tower, or architect Utzon's Sydney opera house being physically realized by engineer Ove Arup. In the present time, the increased use of digital means in the design of the spatial, geometric aspects along with the structural and construction aspects of building, presents an opportunity for increased collaboration and co-authorship of design—i.e., a relationship situated between the domain-general, ambiguous distinction of the eighteenth century and the domain-specialized, hard distinctions of the twentieth century. The use of computers provides a unifying platform between various disciplines, especially in the early *generative* stages of design. Thus, the computational medium allows for the (equal) participation of not only the traditional stakeholders of design process—architects, engineers, and builders, but also other sciences that operate using the medium—mathematicians, biologists, sociologists, etc. The nineteenth-century architect Antonio Gaudi could draw *inspiration* from the biological ideas and drawings of Ernst Haeckel, or develop an artistic repertoire *influenced* by the formal appearance of new mathematics of the time.[12] Contemporary computational designers, on the other hand, can use the very biological models that *generate* our physiology to produce geometry of architecture.[13] They could, in equal part utilize the code of complex mathematics to *generate* structural systems as in the Beijing water-cube stadium.[14] However, legally and in the final execution of the projects, hard distinctions are productive and necessary. Thus, digital technologies can allow for fluid transition from a co-authoring early stages to a collaborative, specialized later stages of design and execution.

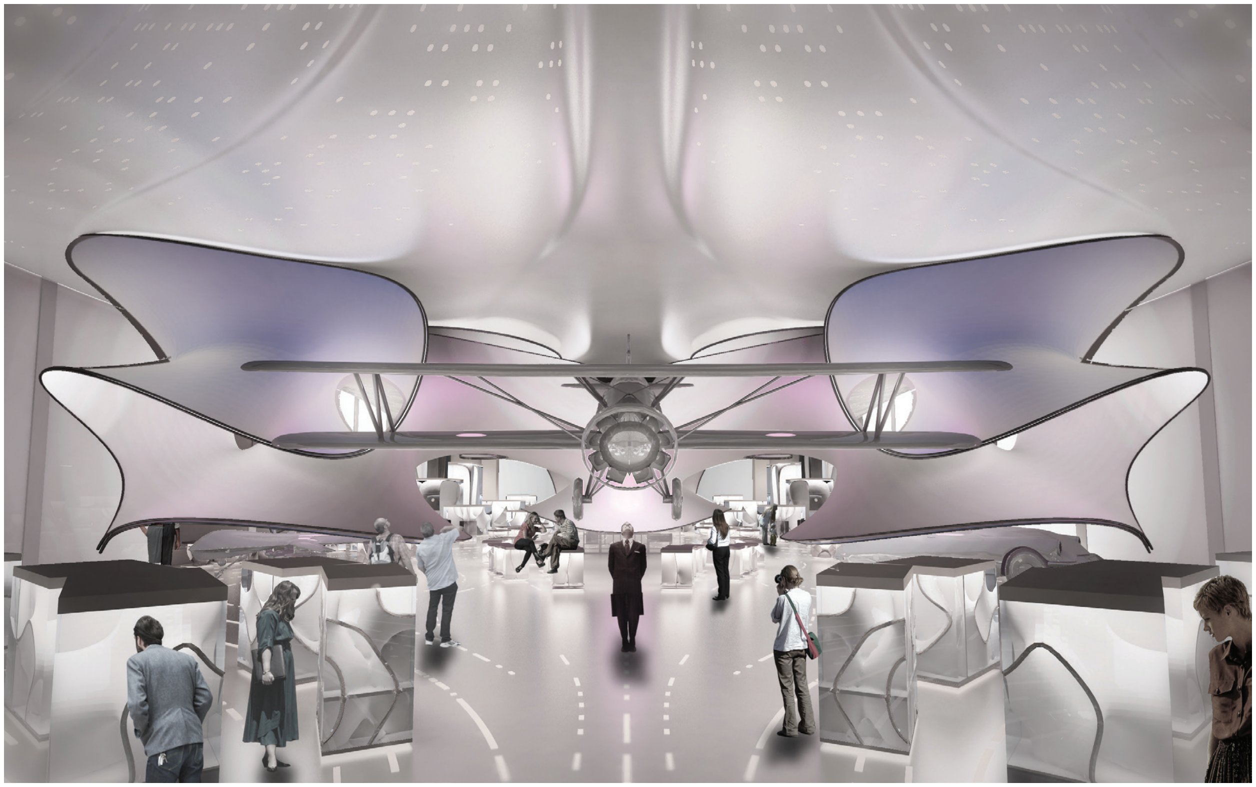
Exemplar Project: The Gallery for Mathematics and Computing

> *The Analytical Engine weaves algebraic patterns, just as the Jacquard loom weaves flowers and leaves.*
> —Ada King Lovelace

The design atelier of Zaha Hadid, founded in 1979, was an early pioneer in and adopter of both these key necessities of innovation—systemic knowledge generation and collaborative design. The Computation and Design research (CoDe) group of the company was an effort initiated in 2007, in line with the preceding pioneering efforts of the company. The explicit aim for the research and development efforts of the group was to harness the opportunities latent in the inter-disciplinary collaboration of computationally literate architects, engineers, and emerging digital manufacturing methods. The atelier has now grown into a large firm with several seminal built projects in this new paradigm of *Parametricist* architecture. It would only be fitting to describe one of the latest projects to embrace the ethos—the design for the Mathematics and Computation Gallery at the Science Museum in London, to be completed by November 2016. We, the CoDe team, started work on the gallery, by a wonderful coincidence, in the bicentennial year of birth of Ada Lovelace, a pioneering woman in the history of computers and of "poetic science"—a resonant desire for a synergetic union of man and machine, articulated more than two centuries ago. The project is a testament to the aforementioned critical aspects of innovation, collaborative design processes, and the fluid exchange of means, methods, and models across disciplines.

Conception of Design

Central to any gallery is the curatorial vision and the objects themselves. The architecture augments this vision, spatially supplements the narrative, and amplifies the assimilation of the information presented. It is therefore natural to make the objects and the narrative into the motivating driver for the spatial organization of the gallery. Additionally, if the objects changes, the spatial organization has to accommodate. The approach to this was a data-driven one. The first step was to tabulate the data—the data of the 100-odd objects, their 80-odd showcases, and their relation to their principal storyline as also the remaining 25 storylines, their position within the six categories, dimensional information, sensitivity to light, requirements of preservation, etc. Next, was to format the data to



enable consumption by a data-processing algorithm. A bespoke algorithm then processed the information and laid out the objects to negotiate the often disparate requirements—curatorial vision, object dimensions, ease of navigation, available space, access and circulation requirements, construction costs, etc. This enabled the spatial layout of the gallery to be changed easily, were the objects, stories, or any another aspect of the curatorial vision to change. This is often the case to accommodate several vagaries and multitude of stake-holders involved in the commissioning, design, execution, and maintenance of a permanent exhibition. Additionally, such a process enables easy measurement of critical performance criteria of the proposed layouts. Apart from the functional metrics such as structural and material feasibility, we were principally concerned with the user-experience of the space. The visual field of an average visitor across several possible access routes were routinely studied and the spatial layouts adjusted accordingly. Primary user navigation and storyline distribution is naturally emphasized using spatial and easy-to-register aspects such as curvature, fluid, and interrupted visual field, etc. This obviates the need for way-finding signage. This is further accentuated by resonance in several other ancillary features such as the lighting and floor tile layout, color scheme, and height distribution of the showcases. All the major features of the space thus become inter-correlated and cohesive with the human navigation and occupation of the spaces.

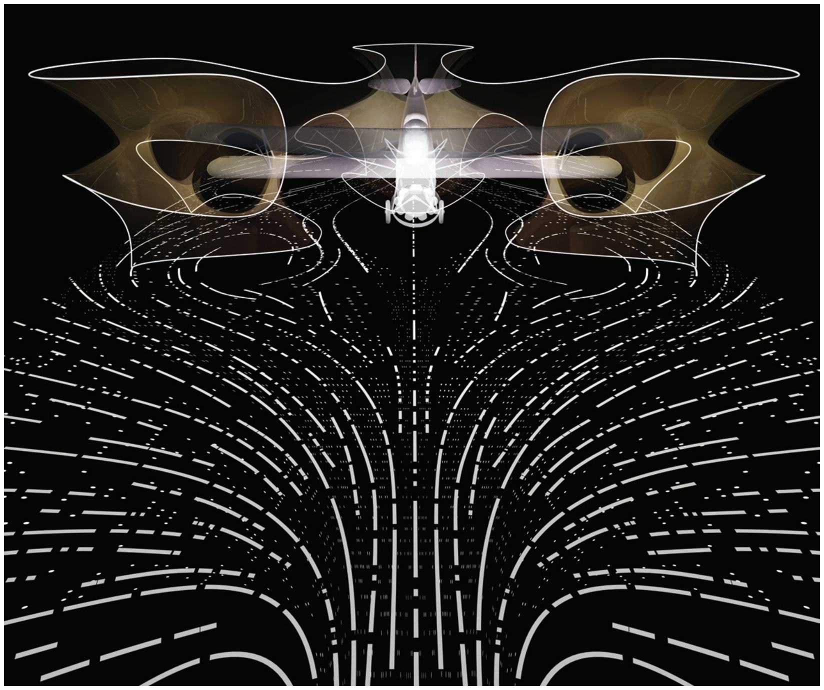
Technology of design and construction

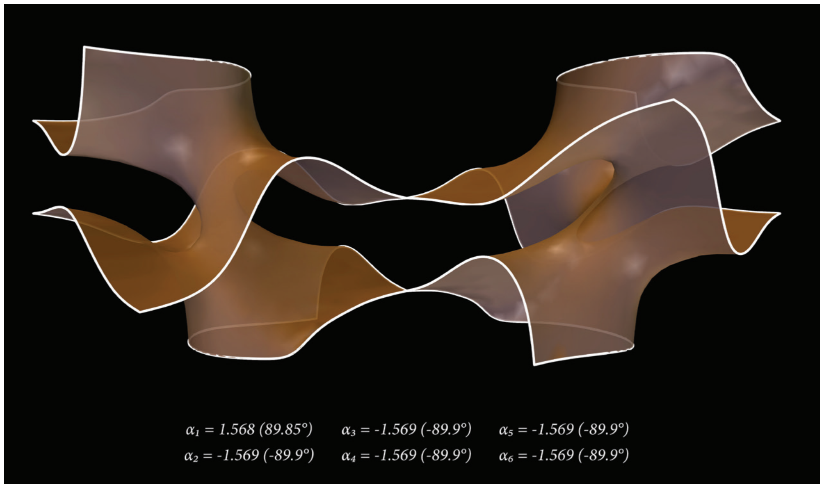
Two specific features—the central fabric structures and the bespoke seating design—of the gallery are worth mentioning in the context of historic *knowledge of design and construction*. These also highlight the need for innovative design to follow a *research program,*[15] as opposed to ad-hoc solutions to design tasks. Imre Lakatos, a philosopher of mathematics and science, used the word – *research program*—both in pragmatic terms of cultivating experience and also the philosophical

sense of maintaining a set of core-beliefs (about design in this case).

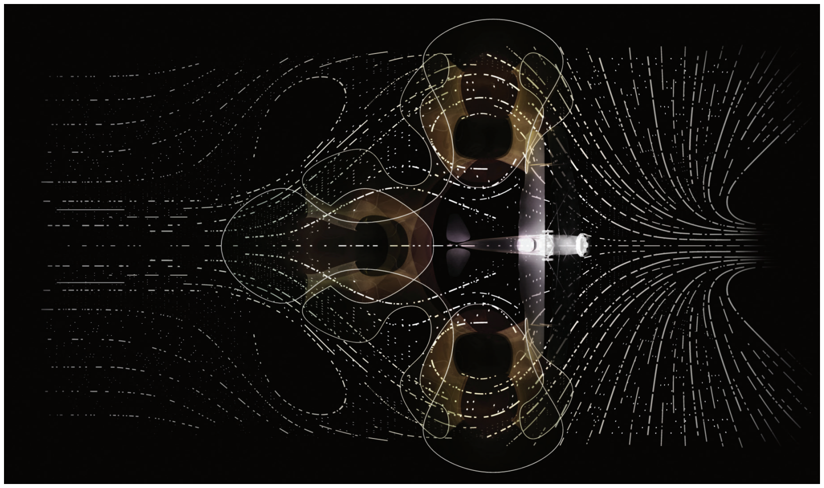
Fabric Structures

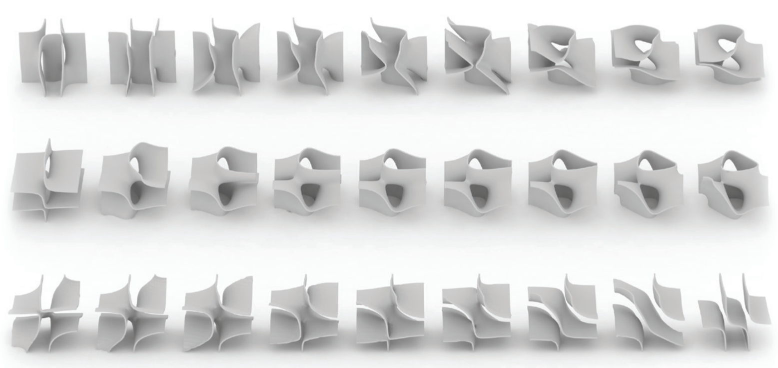
The geometry and materialization of these central organizing features of the gallery are a result of both practical transfer of knowledge across disciplines and also lineage fabric structures that the office has undertaken in the past. The geometry of these constructs—so called minimal surfaces—were intensively studied by pioneering architect-engineer Frei Otto. He studied them physically as soap-films that form against a given wire boundary. These geometries have also been studied mathematically.[16] Their computational *generation*—a so called form-finding process—usually employs one of two popular methods—the force density method[17] and the dynamic relaxation method.[18] These seminal methods have been made more accessible to architects and engineers alike by research institutions like Block Research Group[19] and University of Bath,[20] their architectural materialization as stretched cable and fabric forms has been studied by several architectural and engineering firms, including ours. Prominent prior examples include the seminal Munich Stadium by Frei Otto, and the temporary Serpentine Pavilion (London), the Magazine restaurant (London), and the interactive *Parametric Space* installation (Copenhagen) by Zaha Hadid Architects. Thus, the latest



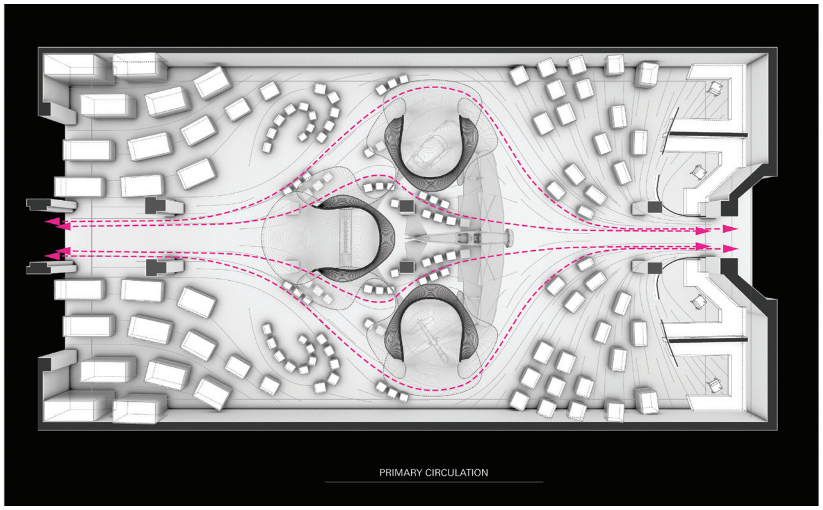


Study of 3D Surface Variations





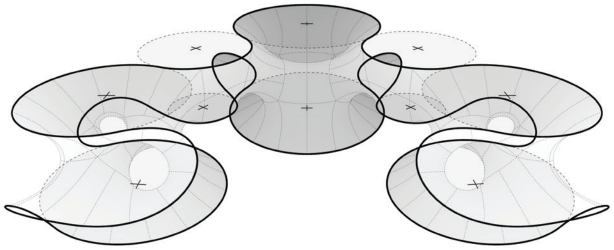
Display Case Forms

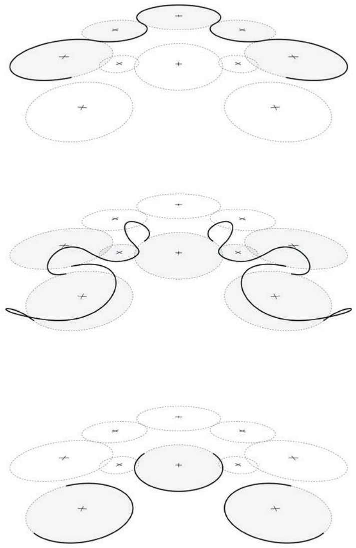


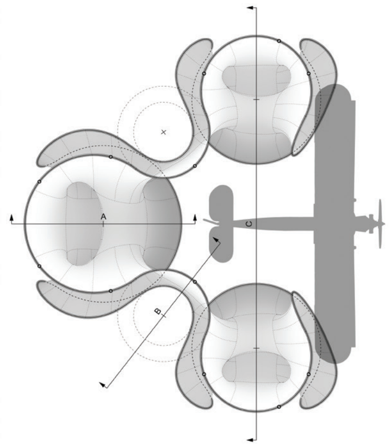
manifestation of such structures in the Mathematics Gallery is a result of a long history of prior experience and historically assimilated and transferred research.

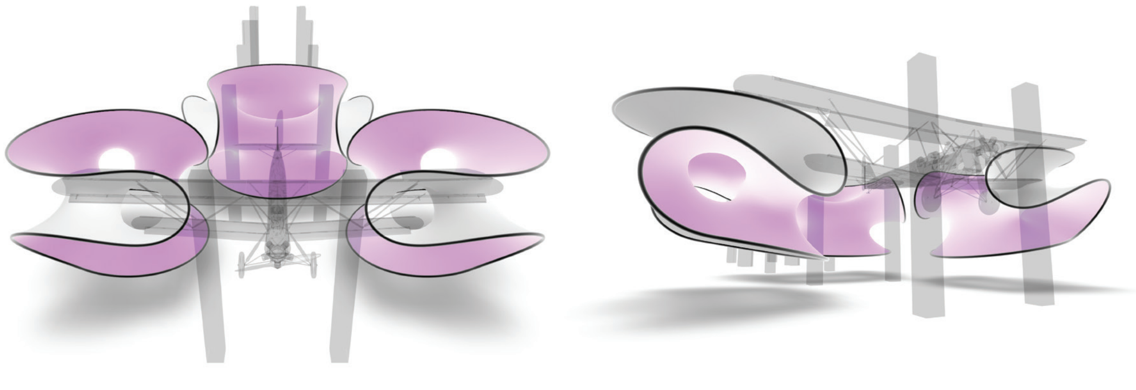
Wire-Cut Concrete Benches

The gallery has several moments of "pause" including fourteen benches—designed as cast, ultra-high performance concrete benches. The shape and physical production of these furniture also owes its development to a long lineage of research in the mathematics, engineering and materialization of a certain class of surfaces called ruled surfaces. Mathematically these surfaces have been known for centuries but its in depth study gained traction after the invention of calculus and is widely credited to French mathematician Gaspard Monge.[21] As mentioned in the introduction, such in-depth mathematical knowledge was abstracted and captured as drawing machines and construction manuals during the nineteenth century.[22] These inventions, in turn, made them widely accessible and their materialization in stone and timber significantly more feasible. These were very prominent and widely used in the nineteenth-century masonry and timber structures[23]—perhaps most famously by the Spanish architect Antonio Gaudi, in his church for the Sagrada Familia, Barcelona. The gallery benches inherit this mathematical, physical, and material history and employ it in a contemporary setting including a collaboration with state-of-the-art robotic company specializing in hot-wire cutting of foam[24] to produce the molds for the cast concrete.



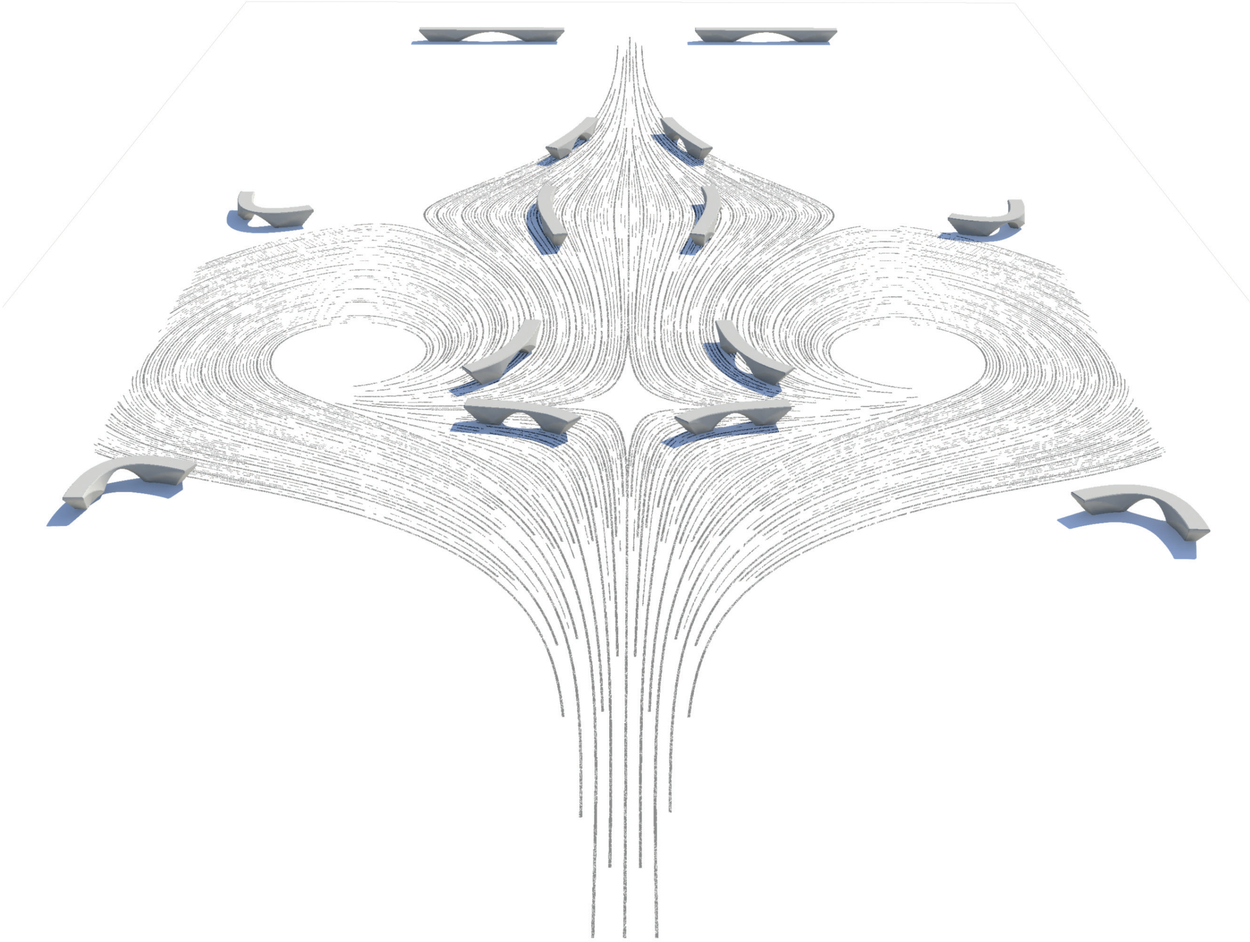






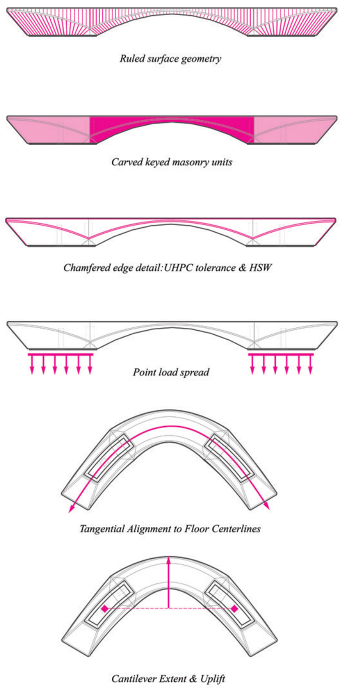
Wire-Cut Benches.

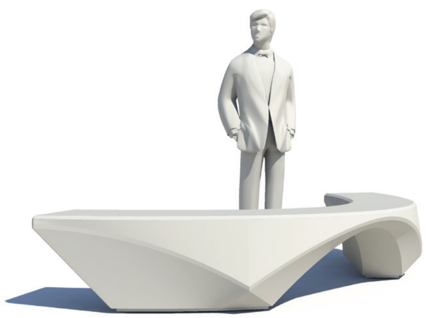
These central, organizing structures of the gallery for Mathematics and Computing at the Science Musuem, London are a result of several years of collaborative projects, research, and prototyping by ZHA and its collaborators and consultants. The design unifies historic methods of form-finding with contemporary design and manufacturing technologies. (Specialist contractor: Base Structures).

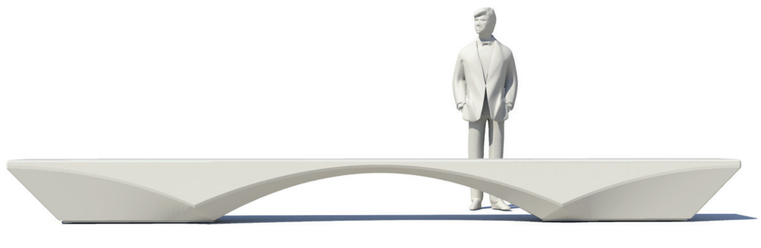


Collaborative Design

As mentioned previously, the computational methods employed to generate the shapes and spaces of the gallery, especially in early stages of design, were a result of a fluid exchange of means, methods, and models across disciplines. For instance, the simulation of the airflow around the key figuring object of the Hadley Page airplane has a lineage in the physics of fluids dynamics going back to Gabriel Navier and Claude Stokes in the 1840s. They were made further accessible and amenable for use in early, interactive stages of design by sustained research in computational fluid dynamics by the likes of Jos Stam,[25] Ron Fedkiw,[26] and others from the computer animation and graphics industry. Thus we were able to utilize the actual models and code as opposed to merely drawing inspiration from the formal appearance of fluid-flows. Similar influences on the central fabric structures have already been mentioned. Such interdisciplinary osmosis in the early stages has now transmuted into more clearly defined roles—architects, engineers, and contractors—in the later stages of the project. Industry standard building information modeling and similar digital technologies are enabling a well-coordinated execution of the project.



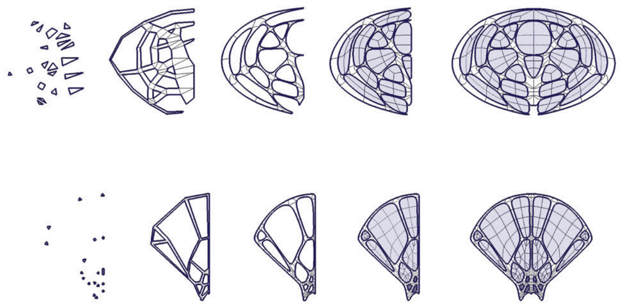


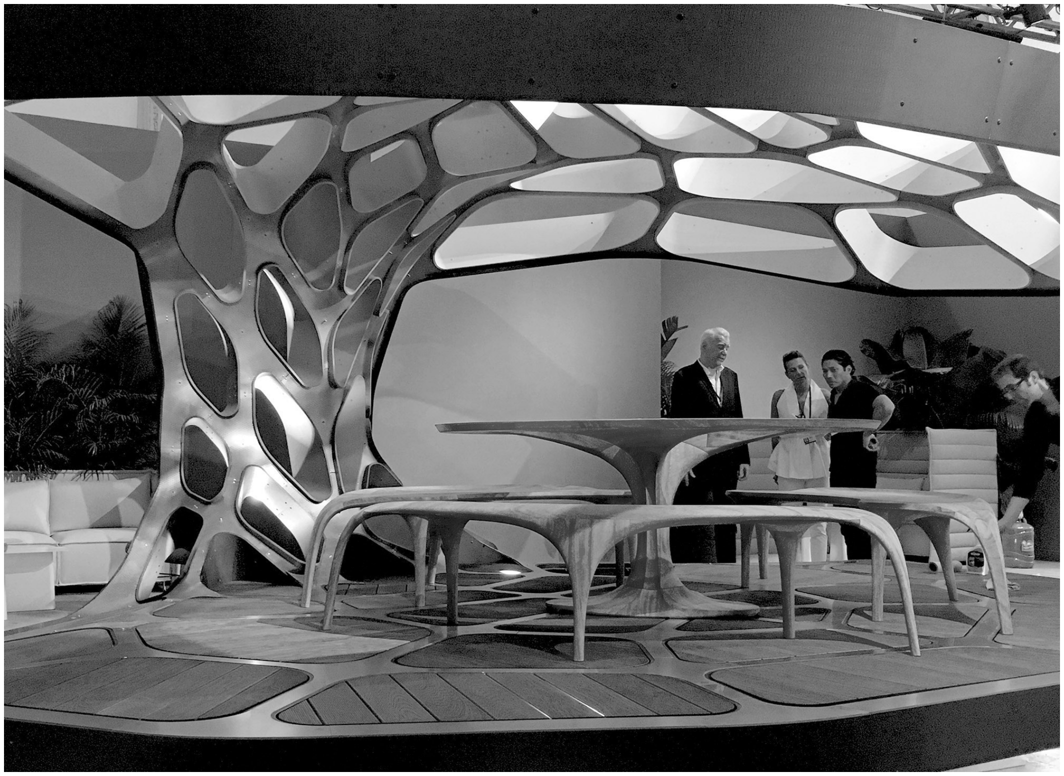


Bench Geometry, Science Museum,London.
The benches are algorithmically generated—negotiating ruled-surface geometric constraints with motion limitations of an industrial robot, and manufacturing constraints of ultra-high-performance concrete. The design learns from projective geometry and stone-cutting techniques pioneered in the nineteenth century by the likes of Antonio Gaudi. The formwork for the benches will be robotically fabricated and subsequently cast upon with high performance concrete. This project is a collaboration between ZHA(CODE), ODICO Robotic Formworks and HiCon concrete specialists.

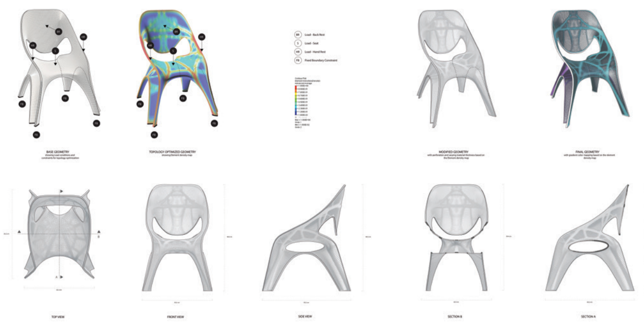
Conclusion

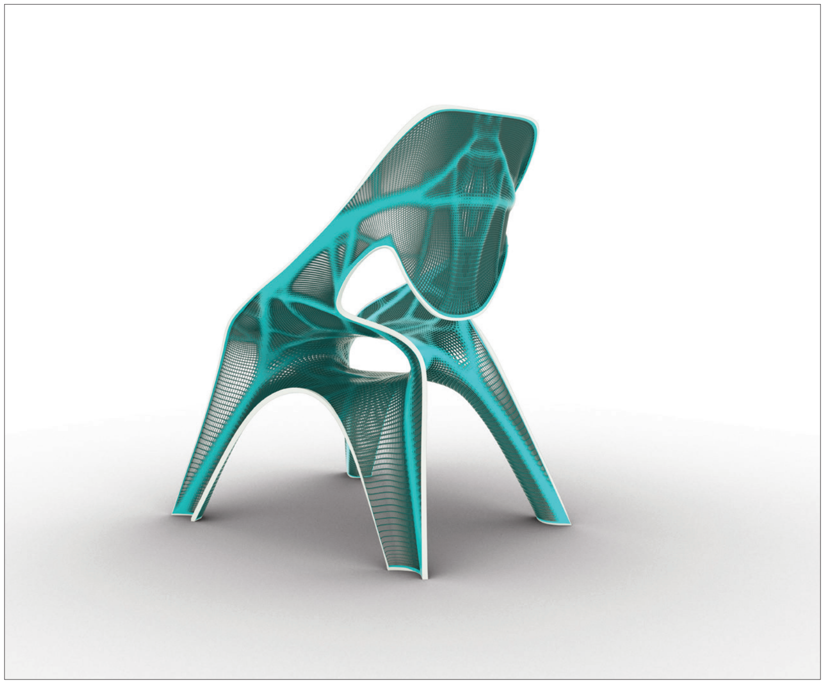
Parametricist or generative design has the potential to overcome the mass-produced, homogenous, and disorienting sterility of twentieth-century architecture. It has the potential to re-associate with historic practice, and amplify assimilated knowledge. It has the potential to heighten the i*nference potential* of spaces—of enabling meaningful occupation and navigation of spaces by humans. To fulfill this potential for rapid evolution of our discipline and upgrade of our built environment, it is imperative that designers and other stakeholders of architecture, invest in it—invest in digital technologies not just digital means of producing known tropes, invest in making design processes amenable for the use of computers, invest in making materialization of architecture amenable to the use of robots. Digitization of architecture and *intelligence augmentation* of designers is a necessary and imperative path to a superior design intelligence.





Volu.
A contemporary dining pavilion that fuses computational design, lightweight engineering, and precision fabrication, Volu's design embeds the tectonics of its manufacture within the form itself. All the timber elements are produced from flat-sheet material with innovative use of kerf-cuts to bend them into loops. (Specialist fabrication and engineering: OneToOne with Ackermann GmBh)





Prototype 3D Printed Chair.
This research prototype was a result of collaboration between ZHA(CODE), and Stratasys Inc. It incorporates contemporary developments in designer-friendly technologies inherited from the computer animation industry, material-saving algorithms (topology optimization) developed by Altair Technologies and other researchers, with innovations in 3D printing to materialize the same.

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