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Arup: Building the Water Cube

The Water Cube, as we know it today, is a result of architects and engineers working side by side. Without this collaboration, the Bubble Box would not have been possible.

—Mark Butler, former Associate Director and Senior Design Architect at PTW Architects

Landing at Heathrow Airport on June 7, 2009, Arup Principal and Senior Structural Engineer Tristram Carfrae pondered the upcoming dinner for which he had flown over 12,000 miles. Accompanied by four other members of Arup's Sydney office, Carfrae was in London to attend the Royal Academy of Engineering Awards Dinner where the winner of the 40th annual MacRobert Award was going to be announced. First presented in 1969, the Award was given in recognition of successful development of innovative ideas in engineering and was considered one of the most prestigious awards in the field. The Beijing National Aquatics Center, widely known as the Water Cube, had been one of the four finalists for the award. Engineering firm Arup had designed the Water Cube in partnership with the architecture firm PTW Architects, based in Sydney, and China Construction Design Institute (CCDI).

An aquatics center that looked like a box of bubbles, the Water Cube had already won a number of prestigious awards (see **Exhibit 1**). Its monumental presence in modern Beijing was due to the way in which it reflected Chinese traditions while using natural resources efficiently. Its design goals included environmental, social, and economic sustainability. The structure set new landmarks in the fields of engineering and architecture and challenged conventional thinking that higher quality required larger investments and longer time to design and build.

The team's multidisciplinary virtual prototyping and holistic approach to design was a new approach in the design and construction industries. Specialists with different professional training, cultural backgrounds, and personal aspirations had collaborated intensely to create the iconic building. Going over his notes for the presentation he was going to deliver at the Awards Dinner, Carfrae began reflecting on what lessons could be learned, both for other projects the firm would do and for the engineering and construction industry in general.

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Arup

Founded by Sir Ove Arup in 1946, six decades later Arup employed over 10,000 professionals. Initially with offices in London and Dublin, the firm had expanded to establish a presence in Africa, America, Australasia, and continental Europe and in 2009 had more than 90 offices in 37 countries. (See **Exhibit 2** for Arup office locations worldwide and **Exhibit 3** for a list of Arup disciplines.) It was a private firm, with no external shareholders or investors.[a] The company continued to grow despite the harsh economic conditions in 2008 and its revenues for that year reached $1.1 billion.[b] It consistently ranked among the top companies in the industry, being both a preferred business partner and employer of choice.

In the early 1960s, the company created Arup Associates in an effort to demonstrate the revolutionary and, for its time, controversial concept of *multidisciplinary total design*. Arup Associates was a broad-based design practice that integrated architecture, structural engineering, cost consultancy, urban design, and product design within one studio. From its start, it tried to deliver high-quality services by giving equal weight to the various disciplines within the team. During the same decade, Arup opened an office in Sydney, Australia, to work on the structural design of what was to become one of the country's most symbolic buildings: the Sydney Opera House. The project was completed in 1973 and, along with other ground-breaking structures such as the Centre Pompidou in Paris, established the firm's reputation for innovation.

In the firm's fourth decade, Arup made sustainability a part of how it did its work. An increasing concern for energy use, efficiency, and conservation resulted in the additional requirement of low-energy designs. The firm's commitment to this issue was formalized with the formation of Arup Environmental Group in 1987. The following year saw the completion of another innovative structure in Australia, the Sydney Football Stadium. With its cutting-edge design and revolutionary curved cable-stayed roof, the Stadium became Arup's first major sports facility in the Southern hemisphere.

Around the same time, Arup Australasia had more than 300 staff consisting of engineers, planners, project managers, and a wide range of specialists including management consultants and software developers. The company had worked on a number of award-winning structures and was repeatedly cited among the leaders in the field not only for the region, but also worldwide. By 1993, Arup, together with PTW, had gotten involved in the design of the Sydney International Aquatic Center, which was to host the swimming and diving events for the 2000 Summer Olympics. It was this involvement that made the two Australian firms strong candidates for the design competition for the XXIX 2008 Olympics being held in Beijing.

Beijing and the XXIX Olympics

The countdown for the XXIX Olympiad started on July 13, 2001, when the International Olympic Committee in Moscow chose the Chinese capital to host the Games of the 2008 Olympics.[1] By the end of the following year, Beijing State-owned Assets Management Co. Ltd (BSAM) had become the nominated owner of the National Aquatics Center where the swimming, diving, and water polo events for the Games were to be held. This was announced in a press conference which also gave the start of the international design competition of the swimming center. "The fact that the Chinese

[a] Arup was owned in trust and each employee was given a share of the firm's operating profit for the year.

[b] Financial data are in USD.

regulatory authorities opened the competition to international participants was of huge significance," reflected Carfrae. Unlike the last two Olympic cities—Athens in 2004 and Sydney in 2000—that had kept the doors closed for outside contestants, Beijing sought to attract experienced design firms to create world-class Olympic venues and provide innovative solutions to the Chinese capital's problems. Increasing air pollution from numerous factories and coal-fired power stations, increasing traffic volume and congestion, a shortage of water, unstoppable migration from villages to the city, and continuous urban expansion were only some of the challenges that had to be addressed. The name of the Olympic precinct—"The Olympic Green"—thus came as no surprise.

The international competition for the Aquatics Center encouraged Chinese design companies to look for Western partners and vice versa. A bi-directional search brought Arup, PTW Architects, and China State Construction and Engineering Company (CSCEC) together. "We sent some of our people to Beijing to explore the possibilities for joint ventures with local firms and China State had sent representatives to Sydney," recalled Butler; "We were in a way looking for each other." Ultimately, it was Arup and PTW Architects' experience with the swimming facilities for the Sydney Olympic Games and PTW Architects' involvement with the XXVIII Olympics in Athens that made them an attractive partner for CSCEC, which at the time of the competition was China's largest construction company. The Consortium was formed in early 2003. CSCEC then brought in China Construction Design International (CCDI), a Shanghai-based architecture firm and a part-subsidiary of CSCEC.

Thirty-three design firms and design consortiums—representing 12 different countries including Australia, Denmark, France, Germany, Greece, Holland, the United Kingdom and the United States—participated in the competition.[2] With the approval from the Beijing Municipal Government, 10 design firms/consortiums were selected to continue to the final round.[3] The Consortium of Arup, PTW Architects and CCDI was among the 10. The teams had 10 weeks to submit the final designs. A panel of Chinese and foreign designers and operations specialists was assembled to select the top three designs. The winner would then be decided through a public vote.

The design of the National Aquatics Center had to meet Olympic requirements, which included a 50-meter competition pool, a 33-meter diving pool, and a 50-meter warm-up pool. The main pool hall was to have 17,000 seats and the whole facility had to accommodate everything required for the operations to take place during the Olympics. After the Games, the main pool hall was to be reduced to 7,000 seats with other facilities added to make the Aquatics Center a facility with at least a 50-year life. The construction was to start before the end of 2003 and be completed at least six months before the Olympics to allow sufficient time for trial competitive events. In addition, the design needed to be in accord with the ambition of the Beijing Olympics to host the best "green games, high tech games and people's games" at world-class venues. Finally, it had to satisfy the objectives of the Beijing Municipal Government who wanted the best Olympic swimming venue that could then become a popular and well-used leisure and training facility after the Games. It also wanted to spend no more than $100 million before the Games and $10 million for its conversion to a public facility legacy mode.

The Concept Phase

The Arup, PTW Architects, and CCDI team agreed early on that the Aquatics Center should portray the way in which humanity relates to water. CCDI sent four of its architects to PTW's Sydney office to make the collaboration smoother and faster. They assisted the partners in communicating design ideas cross-culturally, overcoming the language barriers and preparing documentation for high-level authorities in China. All three firms in the Consortium found instrumental the role of the four CCDI representatives.

At this stage, specialists from different disciplines voiced their expectations for the building. "What was the distinctive difference between this and other projects," Carfrae explained, "was that we brought together our engineers of all disciplines and started brainstorming before the architectural design had commenced." He continued:

> From a mechanical point of view, the best thing we could do was to build an insulated greenhouse. It would be the most energy-efficient solution. The lighting people said they wanted a lot of daylight but not coming straight in because it might bounce off the water and make it difficult for people to see. Structurally, we decided it was going to be steel because of the size of the building. However, we were also trying to minimize the effects of the corrosive environment as much as possible. Ideally, the supporting elements would be neither outside, nor inside the pool hall. Then we had the acoustics, which I still believe had a large influence over the end result. We thought, "How could you make a swimming center sound good?" The water and all the tiles are very reflective to sound and if we were going to build a greenhouse and pursued that option out of glass, it would just make it louder. So, what should we use instead of glass? That was the first time we said ETFE.[c]

Originally developed for the space industry, Ethylene Tetrafluoroethylene (ETFE) had been a product since 1983 but had never been used for major buildings. "At that time," Carfrae noted, "it was becoming more and more popular in small-scale projects in Germany and Holland and it had been used at the Eden Project but that was literally a real greenhouse, not just an enclosure.[d] However, we were also aware that the Allianz Arena in Munich was on the way. Its whole façade was going to be constructed of ETFE air panels." The characteristics of the plastic material ETFE responded to various aspects of the design concept the team had already agreed on. It would provide a cost-effective solution to the greenhouse idea and its transparency would mean sufficient diffused daylight. The fact that ETFE would be able to resist the erosive effects of sunlight and polluted air, could be completely recycled, and would clean itself thoroughly with every rain were additional factors that convinced the team to proceed with the rather innovative material.

The first few weeks of the available design competition period were also spent on developing different concepts proposed by team members. Butler elaborated, "We played around with all kinds of water-related shapes. We had forms that resembled icebergs, waves, soap bubbles, and even waterfalls. Some of these ideas got quickly rejected but others continued to be developed." However, none of the concepts the team had created appeared to be dominant and the design partners struggled to reach a consensus concerning the final form. Around the same time, the Consortium was informed of changes that needed to be made. To free up more room for landscape, the initial rectangular structure area had to be reduced by 30 percent, thus leaving a square footprint of the building.

Gradually two major concepts emerged. A wave-shaped structure that depicted the power of the surf was advanced by the PTW architects, while their Beijing colleagues were in favor of an eroded rectangular form. "It seemed to me," said Butler, "that there were two camps: the Chinese designers stuck on a square based form and the architects at PTW developing a curvaceous building." James

[c] Ethylene Tetrafluoroethylene (ETFE) is a transparent polymer that is very lightweight and has a life span of over twenty years. A close relative to the common compound PTFE—also known as Teflon—it shares some of its properties: it is very tough, has a "non-stick" surface and does not degrade under ultra-violet light, acidic environments or atmospheric pollution.

[d] The Eden Project, designed by Arup Europe, represented a giant botanical garden that consisted of eight domes forming two biomes for trees and plants. It was constructed in a former china quarry in Cornwall, United Kingdom.

Murphy, Vector Foiltec[e] representative who had worked on the Water Cube project as Project Manager and Business Development Manager at CSCEC, commented, "There was a bit of a tension between the Chinese and the Australian designers." Another CSCEC specialist added: "It was almost like two design processes were going on at the same time. The CCDI team was working secretly on their idea and the architects in Sydney were doing their own thing." The architects in Beijing deemed the wave-shaped building to not be a good cultural fit and were trying to secure themselves with an alternative design that was. "The Chinese designers knew in their hearts that this idea [from PTW] was not going to win the competition and wanted to have a back-up plan," summarized a CSCEC representative.

Because of the limited time left before the submission deadline, a decision had to be made promptly. Agreeing on the final form was further complicated by internal disagreement at PTW. "Deciding on the design was especially difficult since our team appeared to be split in two groups," Butler recalled. "Some of the senior staff was clearly supporting the curvaceous design, while others were not entirely convinced that it was a going to be a winning proposal.[f] It was not at all clear how we were going to proceed. What *was* clear was that our Chinese design partners were becoming more and more anxious and wanted a solution."

It was the unveiling of the curvaceous Bird's Nest design for the National Stadium that drove the team to risk everything and proceed with a radically different concept four weeks before the competition deadline.[g] "When we saw the red and curvy structure of the Bird's Nest, we knew that ours was going to be blue and square," recalled Carfrae. The National Stadium was to be on the neighboring site to the Aquatic Center, the two sites separated by a protected historic axis to Beijing's Forbidden City. In an emergency design meeting held four weeks before the deadline, the team members unanimously agreed to abandon the initial design concepts. According to a CSCEC engineer, PTW's Managing Director John Bilmon played a crucial part at this stage since he "persuaded the architects in Sydney to go in the new direction." Ultimately, the design team agreed and moved on. "Throwing the wave-shaped building into the bin was a remarkable and difficult moment considering the time and emotional investment that had been spent developing what was in itself a high-quality solution," said Rob Leslie-Carter, leader of Arup's Water Cube project management team.

At the same meeting, the team agreed on the main components of the Water Cube concept. The building would sit alongside the National Stadium in a harmony reflecting the yin/yang concept from Chinese culture.[h] The Water Cube would seek to portray the harmonious existence of man and nature, which in Chinese culture is life's ultimate blessing. The team also agreed on a flat roof—a feature that symbolizes peace and stability. "From the planning work already carried out on the earlier competition concept, we knew the entire square site would be needed to accommodate the client's requirements, effectively setting a square footprint for the building," explained Leslie-Carter. It was then agreed that a cube concept would appeal to the typical Chinese way of understanding

[e] Vector Foiltec, a German company, was the ETFE design-build contractor selected to install the ETFE cushions of the Water Cube.

[f] The wave-shaped design was originally proposed by PTW architect Andrew Frost.

[g] A team of Arup engineers had collaborated with architecture firm Herzog & de Meuron on the design for the National Stadium.

[h] In Chinese philosophy, yin and yang represent the opposites of the universe. Yin symbolizes the principles of femaleness, the earth, completion, and darkness, while yang symbolizes the principles of maleness, light, heat, and the heaven. Traditionally, the earth is depicted square and the heaven is depicted round.

beauty—a subtle, thought-provoking design representing the beauty and serenity of calm, undisturbed water. As a counterpart to the exciting, energy-giving, masculine image of the Bird's Nest, the Water Cube would appear as serene and emotionally engaging, with changing moods that responded to people, events, and changing seasons.[4]

The final piece of the jigsaw puzzle was provided by Carfrae who did extensive research to find out how structure would or should inhabit space. This is analogous to how space could be partitioned into cells of equal volume with the least area of surface between them. The research was prompted by the fact that two layers of ETFE cladding were required to provide sufficient insulation. This allowed the structure to be placed in the cavity that was formed between the two layers of ETFE. As the structure was the only thing occupying this cavity, Carfrae was interested in how it ought to do so. The search brought him to the Weaire-Phelan foam structure, the best-known solution at the time.[i] (See **Exhibit 4** for more information on the geometrical structure and its application to the Water Cube.) It was the same structure that nature used for living cells, mineral crystals, and even soap bubbles. "We suddenly thought, " Carfrae said, "it was not only going to be made of things that looked like bubbles but the geometry of the whole structure was to going be based on the geometry of bubbles." The recurrent natural structural geometry he found created the Water Cube structure, and its external and internal appearance.

From the Concept to the Model

The Eureka moment for the Water Cube had arrived late in the design competition process. Nonetheless, the team was united behind an idea that they believed could win the international design competition and one that responded to all the architectural and engineering requirements for a premium, sustainable Aquatics Center. The race was on to articulate the idea in a way that would appeal to both the competition judges and the voting public. In the final three weeks of the competition, the concept had to be completely modeled digitally in three dimensions and a physical model created. "With the square shape and the bubble structure, all ideas we had previously discussed came together. We now had to make it work," said Butler.

The rules of the design competition required a physical model of the building to be presented. IT specialists and 3D technicians experimented with different digital models to visualize the concept. The geometry was first generated as a wire frame model by manual repetitive methods in a 3D CAD package. Scripts were then written to add an approximation of the physical member sizes and connections to the centre lines. A technique called Rapid Prototyping was adopted to construct the physical model from the virtual design.[j,5]

Unlike a traditional approach in which architectural design was restricted by the boundaries of structure, the Water Cube was trying to demonstrate that the structure could be an element of the design. Leslie-Carter noted, "This was the first time such a complex physical model had been made using this method. The fact that, despite the timeframes, we were able to successfully deliver it before the closing deadline was a result of a complete team effort. The engineers, the IT specialists, and the architects all came together to produce a coordinated system of modeling." The physical model of the Water Cube was delivered to the Chinese capital on June 17, 2003, three days before the deadline. An

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[i] As of 2009, a better solution than the Weaire-Phelan structure had not been found.

[j] The model was created from a process called SLT (stereolithogtaphy) in which liquid epoxy resin was solidified by a laser following the STL file information to give a semi-transparent robust plastic model.

international panel of 52 preeminent designers, experts, and academics from around the world evaluated the 10 submissions. After nine days of closed evaluation, three designs were selected for public view at the Beijing International Exhibition Center: a design by U.S. firm Rafael Viñoly Architects, a design by Design Institute Shanghai, and the Water Cube design by the Consortium. In the end, the design by Arup, PTW Architects, and CCDI was the clear winner of the international design competition, receiving over one million votes from the public—more than 10 times the votes for its nearest rival.[k]

Turning Vision into Reality

Having won the design competition, the Consortium faced a significant challenge. "The concept itself had an enormous wow-factor," Leslie-Carter said. "It was based on solid engineering factors, but many of the concepts were so cutting-edge that multiple streams of research and development were still needed to prove the design to the Chinese regulatory authorities and to ourselves."

The construction budget, which had been set before the competition, included non-flexible start and completion dates and a fixed budget of $100 million for building the Olympic venue, plus an additional $10 million for converting it to a leisure facility with training and commercial spaces post Olympics. A considerable part of the money needed to fund the project came from donations. The building would be entirely owned and run by state-owned BSAM. Operating on a not-for-profit model, the post-Olympic facility was expected to generate sufficient revenues to operate for at least 50 years.

The design contract specified the division of labor between the design partners, with Arup and PTW architects involved primarily in the concept and design stages and responsible for handing over the design to CCDI to produce the construction documents. This arrangement was in part due to the client's efforts to limit the overall fee bid by sourcing elements of the detailed design and site supervision locally from Beijing. Arup's proposal to maintain a supervisory role during construction to help ensure that the design intent was achieved was seen as an unnecessary cost by their Chinese partner and was not agreed to. Most importantly, the design team had to convert a highly ambitious concept into a developed design supported by full calculations to be submitted to the Chinese authorities within four months.

The "Hi-Tech" Water Cube

Development of design and documentation drawings required considerable collaboration amongst team members. Various disciplines came together through custom-developed scripts and tools to develop the whole model and design drawings. The Arup team used a technique called Building Information Modeling (BIM). BIM had the capacity to attach building information to the 3D digital model thus allowing for a seamless exchange of information between architects, engineers, contractors, and various stakeholders. Creating 3D representations of the various stages of the design process and simulating real-world performances, BIM was used to streamline the process and enhance the quality of the design solution. Among the major BIM-related issues in the Water Cube project were the conceptual design, structural optimization, thermal performance, mechanical

[k] During the competition, the design concepts had names that did not reveal their origin or designer. The "Water Cube" model was "Plan B04".

systems operation, lighting analysis, fire and smoke modeling, drawings generation, and generating the tender documentation used in the materials procurement process.

During the competition stage, 3D modeling was used, among other things, for analyzing the geometrical data and producing a physical model of the structure. After the centerline 3D digital model had been created for the design competition, it was given to structural engineers who had to invent a whole new procedure in order to iteratively perform multiple detailed analyses to determine suitable sizes of the beams, columns, and related structural components. The building would require 22,000 steel beam elements linked through approximately 12,000 spherical node elements. "Since all elements were interconnected," elaborated Carfrae, "changing the size of one element would affect the sizes of the other 21,999. To work this out mathematically, you needed the support of a computer that just the year before would not have been readily available. I do not mean the super powerful computers at universities but ordinary computers that engineering firms like ours have."[6] The iterative procedure determined the minimum size of each steel element so that it satisfied all design requirements and resulted in minimum structural weight.[7]

This novel structural optimization technique turned out to be especially useful four months after the competition was won when, due to budget reductions from the Beijing government, the size of the Aquatics Center had to be decreased from 194x194m^2 to 177x177m^2. Through BIM, everything was rearranged in a timely manner and none of the components included in the original design were eliminated.[l,8] The program also allowed 3D models to be easily exchanged between team members so information could be readily shared. Since the same geometric data could be used to construct different virtual prototypes to be considered at the same time by different specialists, the design team could achieve a more efficient and better-coordinated design process that led to better building performance through the optimal use of materials. (See **Exhibit 5** for a graphical representation of the process.)

In the subsequent construction phase, a conversion program to assist with the construction drawings was developed as part of the BIM design process. It guaranteed that all elements from the structural analysis were transferred to the software package that would generate the construction drawings in the formats needed.[m] "The software that we used was commercially available and could be purchased by anyone interested. The advantage that we had, however, was that some of our IT specialists knew it pretty well and could write scripts to help us use it in quite an innovative way," noted Stuart Bull, Arup Senior 3D Technician. The program modeled the entire structure in less than half an hour instead of the several months required in doing this by hand and from that integrated model, the design team was able to extract elevations, sections and details for the final documentation drawings. It also allowed the client, potential contractors and mechanical specialists to see different parts of the building in the format they needed. Bull summarized:

> The ability to use this kind of technology was paramount in the project. Over the previous four to five years, software and hardware had become much more powerful and were allowing us to do many things much more quickly. Without this technology and the script-writing abilities of our IT experts, we would not have been able to do all this. We actually tried once to do one drawing by hand. It took us three hours and all we had done was one wall. So, to actually reproduce the entire Water Cube model in 25 minutes with everything in the correct order with correct design features was almost unbelievable.

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[l] Each steel element had six faces and each node had thirty-six face. Each face comprised two triangles which translated to more than one million surfaces to be defined.

[m] The software package that was used was AutoCAD, an Autodesk product for BIM.

BIM also allowed for a continuous exchange of information between architects and engineers in Sydney. "Since our information systems were quite similar," Butler noted, "we could easily exchange files among each other." The modeling software also ensured that the building information was handed over for detailing to the Chinese designers in the correct format and before the deadlines specified in the original contract.

The "People's" Water Cube

At almost any moment during the Games, the National Aquatics Center in Beijing was expected to be used by 20,000 people, including athletes, officials, support staff and spectators. This meant that the building had to be constructed in a way that minimized risks without sacrificing the Olympic experience.

Fire and Façade Engineering Demonstrating that the design provided an acceptable level of safety was an especially challenging task because of both the unconventional structure and the innovative ETFE material. As the Water Cube did not follow the prescriptive requirements of the Chinese Building Code, the design team applied a performance-based approach to convince the Chinese authorities that the building would be safe.[9] Marianne Foley, Lead Fire Engineer for the Water Cube and Senior Associate at Arup explained, "The performance-based design approach is a preferred method for providing appropriate levels of fire safety in unusual or complex buildings that are not covered by conventional prescriptive building codes." Despite its useful insulation and acoustic properties, ETFE was highly combustible and the Chinese Building Code did not allow the use of highly combustible materials. Foley elaborated, "We needed to demonstrate to the Chinese authorities that in case of fire, burning droplets of ETFE would not rain on people's heads, that smoke would vent out of the roof and that the people would be safe." In fact, a main attribute of ETFE was its ability to shrink away in fire, thereby venting smoke out of the building.

Applying the performance-based approach involved complex analyses, the use of research data, and multiple presentations to the Chinese design partner and the Chinese regulatory authorities. "Negotiating with the authorities in Beijing was very important for getting their approval," said Foley, "and CCDI assisted us immensely with the negotiations." The fire engineering design was the first Olympic venue to receive approval for fire engineering and set a precedent for the other Olympic projects in the area.[10]

Safety in Design[11] Safety issues extended beyond the structure of the Water Cube. Arup's project management team committed to exploring the risky activities that could occur during construction of the Aquatics Center and to determining how the design partners could follow a "Safety in Design" approach to lower the risk of accidents. This included producing documentation that would improve safety awareness, and suggesting planned and logical methods for construction and maintenance. "Safety in Design" was intended to ensure that unusual risks and hazards (such as post-Olympic alternations to the internal fit-out and working-at-height hazards involved in maintenance) were eliminated or controlled at the design stage wherever possible.

The "Green" Water Cube

The Water Cube was designed to act like a giant greenhouse. Haico Schepers, a Senior Associate who led the Sustainability Group at Arup explained, "From day one, we wanted to build a greenhouse. Because pools are heavily heat-dependent, we wanted to use the energy of the sun rather than the conventional way of sealing the box and generating heat from the inside using fossil fuels."

This effect was achieved by cladding the building in ETFE cushions which would trap 20% of the solar energy falling on the building. The power of the sun would be used to passively heat the building and the pool water.[12] The ETFE cushions would also allow a large amount of natural daylight into the building. The reduced heating energy consumption for the leisure pool was estimated at 30% with a reduction of 55% in the requirement for artificial lighting.

Apart from reducing energy consumption, Schepers and his team tried to maximize the conservation of water. Water in the region of Beijing was a valuable commodity and the Chinese capital lacked efficient systems for water reuse and recycling. Under the proposed plan by Arup Sustainability Group, 80% of the water harvested from the roof catchment areas, pool backwash systems, and overland flows would be reused and recycled by incorporating water-sensitive urban design principles.[13] Schepers noted, "We were in a sense trying to reduce the reliance and pressures on local water supply systems."

To evaluate the sustainability of different components of the building, Arup used an assessment tool called Sustainable Project Appraisal Routine or SPeAR®. SPeAR® provided an evaluation of the project in four dimensions: natural resources, environmental, social, and economic. The tool also provided recommendations for improvement (see **Exhibit 6**). The use of SPeAR® for the Water Cube was in part prompted by the Beijing Municipal Government which demanded a long-lasting aquatics center that would operate for at least 50 years in a post-Olympic mode, be ecological, and able to sustain itself economically.

Beyond its structural boundaries, the Water Cube contributed to the "greening" of the Chinese capital as a catalyst that encouraged people to consume more efficiently and aspire to improve the environmental conditions of their city. It also served as an inspiring precedent for local and foreign designers aiming for more sustainable design solutions. According to Leslie-Carter, it could act as a "stepping stone from traditional monumental communist architecture to a future more about conserving resources and building more delicately and sustainably."[14]

Managing the Project

Introduced by Arup's founder Sir Ove Arup, the "total design" concept was based on involving all professional design and engineering disciplines from the onset of a project assignment. This was believed to aid the development of a design process in which all design aspects were considered thoroughly.[15] From conception, each project would be carefully considered and assessed by many different disciplines, helping to ensure that overall project objectives were met. Bringing together all the necessary skills and technologies would optimize the building in terms of operation costs, energy efficiency, and environmental quality from design stage to post-occupation. (See **Exhibit 7** for a comparison between traditional design and total design.) Part of the vision of "total design" also included engaging the client in the design process and forming a close relationship with them that would continue beyond the completion of the project.

The design of the Water Cube was based on the "total design" approach. The Arup team included more than 80 engineers and specialists spread across 20 disciplines and offices in four locations: Australia (Sydney), China (Beijing), Hong Kong, and the United Kingdom (London). Specialists from Arup, PTW Architects, and CCDI joined efforts early in the design process and continued to collaborate until late in the process when the design drawings were handed over to the partner in China. "Including all disciplines simultaneously," noted Leslie-Carter, "had enormous benefits.

However, it significantly increased the complexities of the project. These came not only from professional, but also from cultural differences."

To cope with the challenges associated with the "total design" approach, the work on the Water Cube was divided into four major separate but parallel streams: (1) design, (2) product research, (3) stakeholder engagement, and (4) commercial issues such as scope, contracts and fees, which were the responsibility of the Arup project management team. Led by Leslie-Carter, the team was composed of project managers with solid technical backgrounds and well-developed interpersonal and leadership skills. Explained Leslie-Carter,

> The people who were collaborating in the design on a day-to-day basis did not have to get involved in the probably more messy contractual and commercial conversations. At the same time, the negotiations should not affect the design relationships. Our job, therefore, was to orchestrate these design streams and to ensure that they all converge at the end with the common goal.

During a two-day workshop held soon after the Water Cube design was selected, the project management team at Arup developed an implementation plan with strategies to address challenges that arose because of the integrated nature of the work. Some of these strategies included communicating a clear vision, creating a safe design environment, and interface and culture management. (See **Exhibit 8** for a full list of the implementation plan strategies.)

Creating a Safe Design Environment

The four design streams were in part established to allow technical staff more freedom and to remove potential task overload of specific key staff such as senior engineers and associates. Leslie-Carter noted, "Our specialists were dealing with materials and structures that were quite new in some ways. Take for example ETFE or fire engineering or structural optimization. This meant that we had to give our people the freedom to progress and be able to fail and stand up again. We had to give certain people a degree of autonomy so that they can do their work."

This strategy was also a form of recognition on the part of the project management team of another factor that was deemed important for the smoothness of the design activity. Leslie-Carter continued, "In terms of team dynamics and leadership, these are individuals who would typically resist being led, resist working to deadlines, and dislike centralized management structures. Leadership had to show each their respect." Accordingly, the project management team focused on providing these people with a safe design environment where they could experiment and on protecting them from administrative issues. For instance, specialist project managers took responsibility for internal reporting, commercial issues, and coordination of technical interfaces.

Management of Interfaces[16]

The challenges the design team faced included the integration and coordination of the many interfaces for the project—involving multiple stakeholders with conflicting demands. Coordinating the requirements for athletes, officials, VIPs, the press, broadcasters, the workforce, sponsors, and spectators was a complex task and required delicate balance. Drawing on previous work by Arup at London's Heathrow Terminal 5, the project management team introduced a strategy for "interface management" that divided the Water Cube into "volumes" based on physical and time boundaries, as described in a project volume register. Each volume was owned by a sub-project team. An interface occurred when anything touched or crossed a boundary between. Initially, high- and low-level interfaces were identified and captured on a register, and regular interface coordination meetings were held involving all relevant parties.

The interface management approach was applied both internally and externally. The external interfaces were classified in four groups:

- **Physical**: a point or plane common to two or more parties at which a physical interdependency existed. An example of physical interfaces would be an underground services or duct route.
- **Functional**: a relationship between two parties at which performance dependency existed. Examples included power requirements and data connectivity.
- **Organizational or contractual**: a relationship between two parties at which delineation in scope or contractual responsibility existed. An example was the interface between civil engineering and architectural landscaping documentation.
- **Operational**: a relationship between two parties at which delineation of operational responsibility existed. For example, maintenance for equipment under warranty with the ongoing maintenance and replacement by the operator.

The management of interfaces became one of the most important functions of Arup's project management team. According to an Arup project manager, "In the short term, eliminating mistakes at the interfaces meant that documentation was handed over to the Chinese design partner accurately and quickly. In the long term, we believe, it generated one of the largest possible savings in current industry practice."

Managing Cultural Differences

A significant challenge for the design team came from the interaction of two different cultures. Inside the Consortium, the challenge was partially solved by CSCEC establishing roles for CCDI and PTW in the original design contract. Overcoming culture differences was also achieved through exchanging specialists who had familiarity with both cultures. They were instrumental not only for overcoming the language barriers, but also for bridging the cultural differences in norms, practices and expectations throughout the project. Finally, internal meetings attended by representatives of all design partners were held to decide on the team's approach to the management of differences.

These meetings also focused on maintaining contractual agreements and on minimizing risks associated with cultural misunderstanding beyond the boundaries of the Consortium. Beijing's lack of regulatory transparency, different work approaches, and relationship-based business culture were among the factors that the design team identified as challenging in the context of the project environment. The project management team also made sure that all interactions with the Chinese stakeholders such as Government and Olympic officials involved the highest possible quality of service, both in terms of materials that were issued and the staff sent to directly meet with these different stakeholders. Well-respected senior engineers from Arup's Beijing and Hong Kong offices were involved at every key stage of the approval process.

A Quiet Revolution in Building Design?

On June 9, 2009, the 40th MacRobert Award went to Arup for its work on the Water Cube. According to the judging panel, the Water Cube surpassed other finalists in three criteria: innovation, commercial success, and benefit to the community.

The Beijing National Aquatics Center was born in a virtual, collaborative world. Computer-aided collaboration had allowed the design team spread around the globe to complete the design in just six months. The Aquatics Center was designed, tested, and optimized to such an extent that the final Building Information Model was used directly for construction as opposed to previous projects where its use was limited to the concept stage and optimization. The revolutionary use of virtual prototyping was a milestone; it proved that each building no longer had to be tested on the ground, instead all performances were analyzed and optimized in a virtual, digital world using BIM prior to construction. The "box of bubbles" had resulted in an intelligent solution for everyone. The ETFE panels acted like an insulated greenhouse—trapping heat, letting in light, and saving water.

Internal to Arup, the Water Cube had resulted in a satisfied team with an enhanced commitment to "total design." The project was a financial success in that the firm had made an acceptable profit despite the considerable risks of working on a fast-track project, with international partners and stakeholders, on a project involving ground-breaking design techniques and materials. Some of the new methods such as structural optimization and multidisciplinary virtual prototyping had since been used on other projects, including the Grand Egyptian Museum in Giza, Marina Bay Bridge in Singapore, King Street Wharf in Sydney, and the Fulton Street Transit Center in New York City. For Arup in China, the Water Cube and the other Olympic projects the firm was involved in provided a platform for a future expansion in the region. Since 2000, Arup had spread from Hong Kong to Shanghai, to Shenzhen and then to Beijing. In 2009, Arup had eight offices in China and 25% of the firm's global staff was based in its Chinese offices.

More broadly, the "box made of bubbles" changed the way foreign designers worked with Chinese partners. "What was typical until the Aquatics Center in Beijing," explained a Vector Foiltec engineer, "was that big-name foreign architects would come to China with an arrogant attitude that they must be followed and the local Chinese firms should be servants to their design ideas. This did not happen with the team for the Aquatics Center. It was not a brand individual coming into China, but rather a true partnership. And it was more than a partnership, it was co-leadership."

The Water Cube design was the integration of many ideas from many people. These ideas did not arrive fully formed but developed through interaction between professionals with different skills, different perspectives, and different cultural backgrounds. Through continuous discussion and collaboration, they became welded into a seamless design. "It is impossible in retrospect to attribute any single idea or part of the idea to any single person," commented Carfrae. "This is not a design with a single author but more the work of an empowered and well managed collective. What is perhaps surprising is that such a process should result in a building with a very clear purpose—using minimum resources to create a delightful venue, a box of bubbles for swimming."

In transforming this idea into reality, the Water Cube had also challenged conventional wisdom that higher quality needed larger investments and despite the numerous risks, was completed before the specified date in the contract. In the words of an Arup specialist, "It was creating a quiet revolution in building design and proving that sustainable development was no longer an oxymoron." What its impact on the company would be and how this could be best leveraged and managed, were questions that Carfrae and his team would still have to answer.

Exhibit 1 Awards Won by Water Cube

Year	Award
2004	Venice Biennale, 9th International Architecture Exhibition – Award for Most Accomplished Work, *Atmosphere* section
2004	*Building Engineering* and Bentley Systems Inc. – Building Modeling for Architecture and Engineering Award for Excellence
2006	*Architecture Review* Emerging Architecture Award
2006	*Popular Science* "Best of What's New" in Engineering Grand Award
2006	AIA Technology in Architectural Practice – Building Information Modeling Award
2008	AIPM (Australian Institute of Project Management), NSW Division, Project Management Achievement Awards – 'Project of the Year'
2008	AIPM (Australian Institute of Project Management) National Project Awards – 'The President's Award'
2008	Australian Institute of Architects' John Utzon Award for International Architecture
2008	APM (Association for Project Management (UK) Awards) International Award
2008	IstructE Centenary Awards for the Best Sports or Leisure Building
2008	Engineering Excellence Awards NSW/ACT Division, William Bradfield Award
2008	Australian Engineering Excellence Awards – The Sir William Hudson Award
2008	ACEA (Association of Consulting Engineers Australia) National Awards – Project of the Year
2008	China Civil Engineering Society – 8th Zhan Tianyou Civil Engineering Award
2009	*Marie Claire Magazine* "101 Sexiest Things of 2008"
2009	Condé Nast Traveler Design and Innovation Award – Leisure Category
2009	Royal Institute of British Architects (UK) – International Award
2009	Royal Academy of Engineering (UK) – MacRobert Award

Source: Compiled by casewriter with assistance from Arup.

Note: Several specialists and project managers have been awarded individually for their contributions to the project. These awards are not included in the exhibit.

Exhibit 2 Arup Office Locations

Source: Arup.

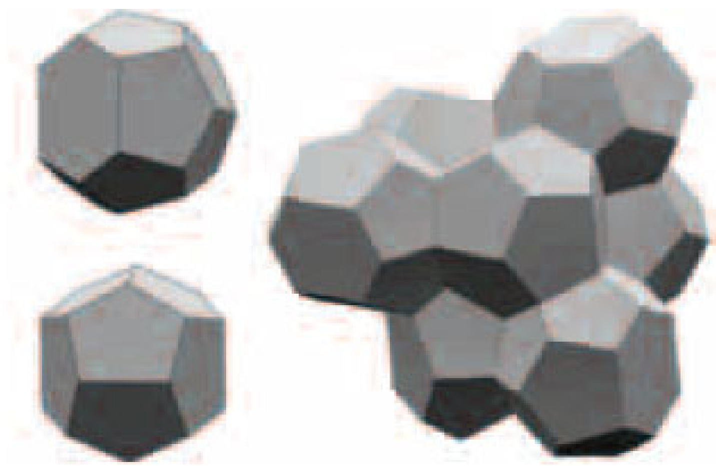
Exhibit 3 Arup Disciplines

- Acoustics
- Aviation
- Civil and Infrastructure
- Electrical
- Environmental Sustainability
- ESD
- Façade
- Fire Engineering
- 4D Staging
- Geotechnical
- Hydraulics
- IT and Communications
- Mechanical
- Pedestrian Modeling
- Specialist Lighting
- Structural
- Transportation
- Virtual 3D Modeling

Source: Arup.

Exhibit 4 Geometry of Bubbles

Arup's Tristram Carfrae was not the first to become curious about the shapes that fill three-dimensional space uniformly. In the late 19th century, the great Lord Kelvin asked: What is the most efficient way to divide space into cells of equal size with the least surface area between them? Kelvin himself proposed a highly regular solution to his own problem. But when he applied the 14-sided Kelvin shape (called a tetrakaidecahedron), it proved visually uninspiring. Nor was Kelvin the first to seek the solution. A century earlier a Belgian scientist, Plateau, had studied soap bubbles and devised rules for the way they join together in three faces forming a line; four lines coming together at the tetrahedral angle of 109.4 degrees. Surely, it would be simple to create the geometry of a continuous array of soap bubbles? This would in turn answer Kelvin's question because surface tension automatically minimizes the surface areas of partitions between the bubbles. At this point, another "But" was found: because Plateau's rules simply cannot be applied to create a geometry that joins together.



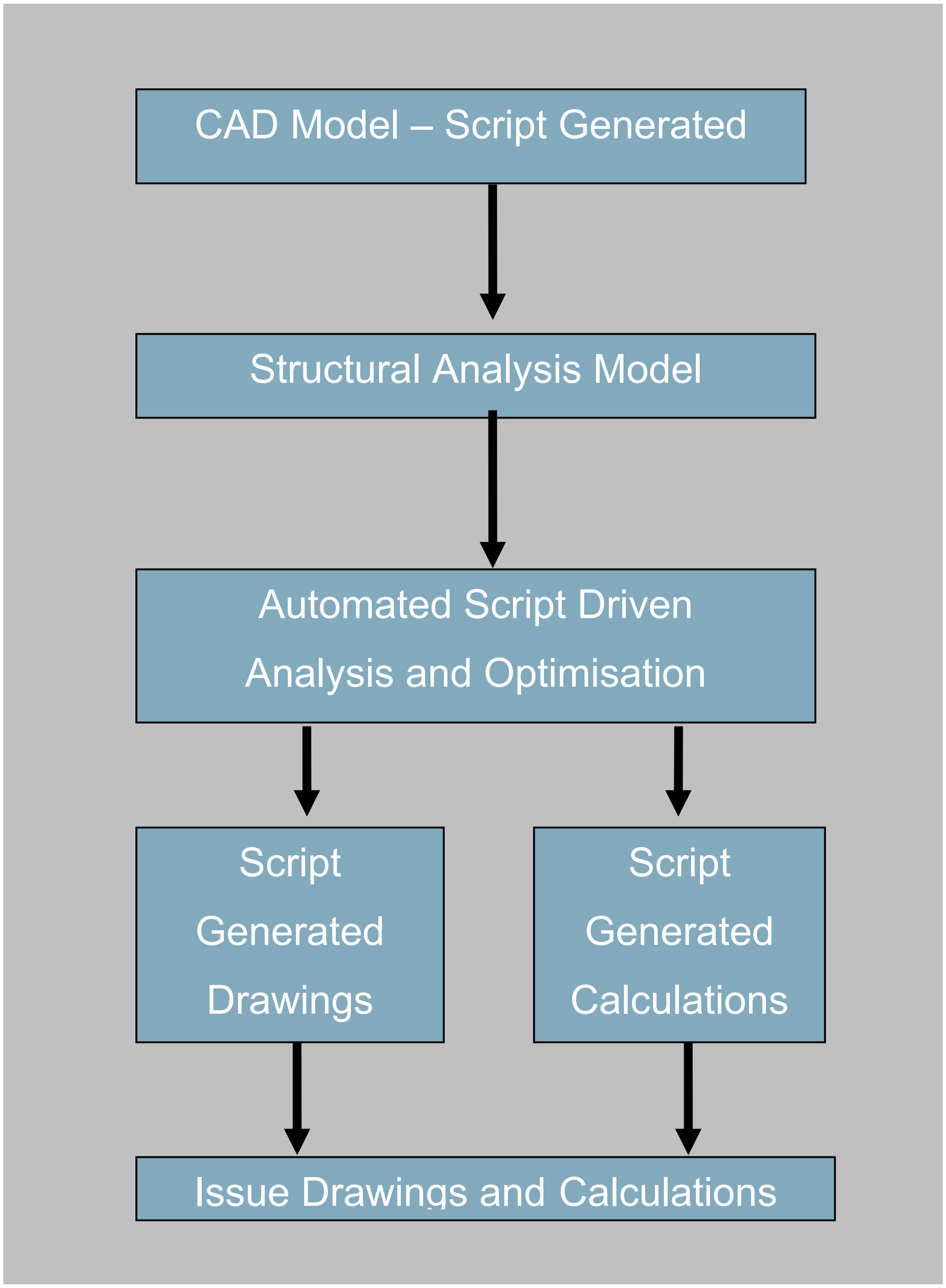
The solution proposed in 1993 by Denis Weaire and Robert Phelan: three quarters of the cells have 14 sides, while the rest are dodecahedra with 12 sides. Both sets of cells have the same volume and it was this principle that was taken up for the Water Cube.

IT Solution: Much more recent research, however, provided the answer. A century after Kelvin, Professor Denis Weaire and his assistant Dr. Robert Phelan at Trinity College used advanced computer programs to help them discover a solution up to 2% more efficient than Kelvin's, subsequently named "Weaire-Phelan foam." A curious feature about this foam was soon found. In spite of its complete regularity, it appeared totally random when viewed from an arbitrary angle.

From the computer screen, the Weaire-Phelan foam was applied to the structure of the Water Cube. The approach to constructing the building began by visualizing an infinite array of foam, oriented in particular way, and then carving out a block the same external size as the stadium, 117m x177m x 31m. The three major internal volumes were removed from this foam block and the result was the geometry of the structure. This would then be clad in ETFE pillows inside and out to gain the desired organic look and to function effectively as an insulated greenhouse.

Source: Carfrae, T. (2007). Box of bubbles. *Ingenia 33*, 45-48. Published by The Royal Academy of Engineering. Provided by Tristram Carfrae.

Exhibit 5 Virtual Prototyping Process as Applied to the Structural Design

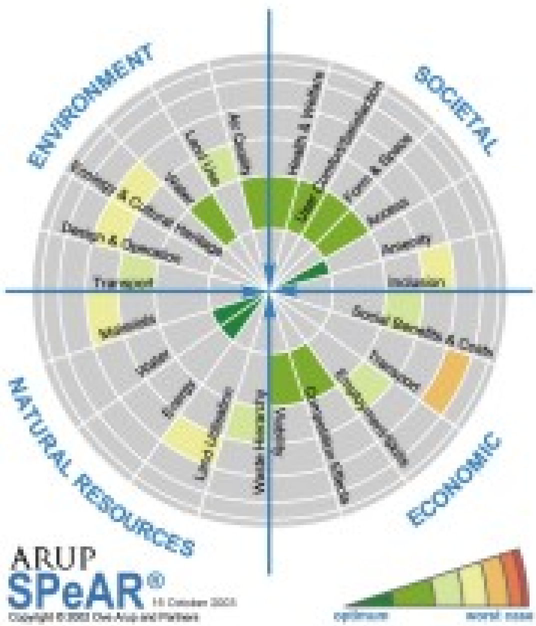


Source: Arup.

Exhibit 6 SPeAR®

Sustainable **P**roj**e**ct **A**ppraisal **R**outine (SPeAR®) has been developed by Arup as a framework to demonstrate the sustainability of a project, product, process, or organization, providing an integrated approach to natural resource management, environmental, economic and social systems.

The tool is based on the UK Government's Sustainable Development Strategy—*Securing the Future* (2005)–combined with the Government's sustainability indicators (Defra, 2004) and those of the United Nations' Environment Program (UNEP) and the Global reporting Initiative (GRI). Together, these form over 120 sub-indicators within the four headline topic areas. By assessing the attributes of a project against these indicators, SPeAR® builds a graphical image of sustainable performance, identifying strengths and challenges.



The SPeAR® Assessment for the Water Cube

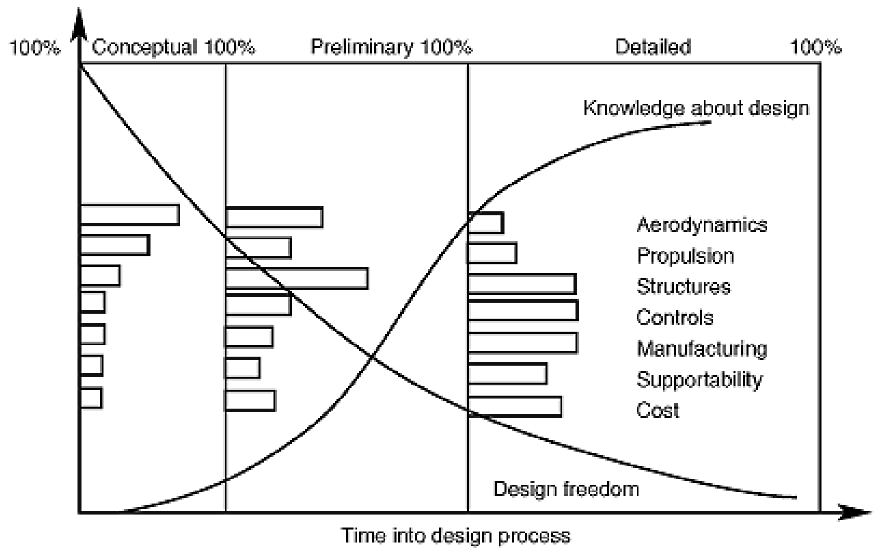
The diagram is read like a dartboard: the closer an indicator segment to the center, the more sustainable its performance. The central white wing equates to compliance with best practice. The tool is useful for providing information to designers, managers and other stakeholders to aid decision making. A set of recommendations emerges through the appraisal process, which together can form an action plan for improvement. Repeat appraisals can facilitate ongoing improvement in performance and assist the delivery of appropriate policies, principles and objectives.

The range of areas in which SPeAR® can be used is continually expanding. Traditionally, applications have included master planning, building design, corporate sustainability strategy, and manufacturing.

Source: Arup.

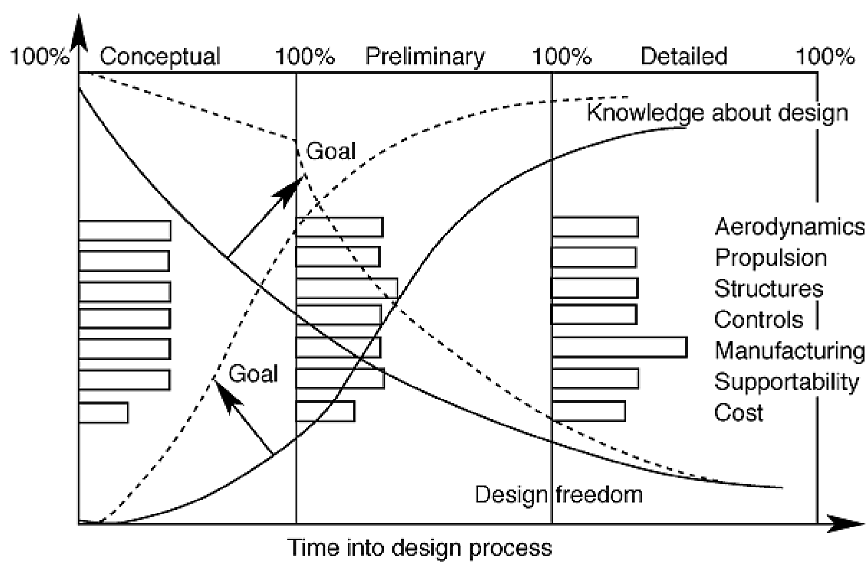
Exhibit 7 Tradiitional Design versus Total Design

Figure A. Traditional Design:



Problems: Short conception design phase with unequal distribution of disciplines does not allow use of design freedom to improve quality and integrate disciplines for optimization.

Figure B. Total Design:



Design process reorganized to gain information earlier and to retain design freedom longer.

Source: AIAA Technical Committee on Multidisciplinary Design Optimization. White Paper on Current State of the Art. January 15, 1991, http://endo.sandia.gov/AIAA_MDOTC/sponsored/aiaa_paper.html, accessed February 2010. Figure A corresponds to Figure 5 and Figure B to Figure 12 from the paper.

Exhibit 8 Implementation Plan

1. Crystal clear vision for the building design that would allow parallel steams of activity to converge quickly and accurately, and help achieve alignment and buy in from other project stakeholders.
2. A detailed strategy for internal and external communication.
3. Develop original planning and monitoring systems capable of tracking the performance of such a large and geographically diverse team in real time.
4. Lead and manage large multidisciplinary team including an unusually high proportion of very detailed analysts, capable of pulling together to deliver the fast-track design of such a complex Olympic venue.
5. Ensure fully interfaced between 20 Arup disciplines and the architects, and robust enough for handover to our design partners for detailing.
6. Establish semi-independent teams to progress the design, product research, and stakeholder engagement in parallel, to remove potential pinch points from specific key staff becoming overloaded.
7. Drive a Safety in Design Agenda, to proactively reduce risks during the construction, operations, and future alternation of the building. This is particularly driven by China's poor safety record, and the likely accelerated timeframe for the building's construction.
8. A risk management strategy focused on the complex and dynamic nature of the Chinese market, and the "management of difference between" Australian and Chinese stakeholders.
9. Actions to ensure the contract, fees, and scope of the services are unambiguous, clearly understood by all parties, and adhered to for the duration of the project.

Source: Arup.

Endnotes

[1] "The Olympic Games en route for Beijing," Beijing 2008, http://en.beijing2008.cn/news/official/ioc/n214110795.shtml, accessed May 20, 2009.

[2] "The National Aquatics Center, Timeline," Beijing 2008. http://en.beijing2008.cn/87/37/article212043787.shtml, accessed May 20, 2009.

[3] Ibid.

[4] Pohl, E. B. (2008). *Watercube: The Book*, 80-81.

[5] "The Structure," Arup Australasia, Arup Web site, www.arup.com/australasia/ feature.cfm?pageid=3460, accessed May 30, 2009.

[6] The quote is based on an interview with Tristram Carfrae in the documentary film "Honey and Bubbles: A Story of the Water Cube" (2008), commissioned by Arup and produced by G2 Studio.

[7] "The Structure," Arup Australasia, Arup Web site, www.arup.com/australasia/ feature.cfm?pageid=3460, accessed May 20, 2009.

[8] Ibid.

[9] "Protecting The Water Cube," Arup Australasia, Arup Web site, www.arup.com/australasia/feature.cfm?pageid=3778, accessed May 21, 2009.

[10] Ibid.

[11] This section draws on "National Aquatics Center, Beijing (The Water Cube): Award for APM Project Management Awards 2008," Arup, internal document, 2008.

[12] "The Giant Greenhouse," Arup Australasia, Arup Web site, www.arup.com/australasia/feature.cfm?pageid=3491, accessed May 21, 2009.

[13] "The Water Cube: a Sustainable Venue," Arup Australasia, Arup Web site, http://www.arup.com/australasia/feature.cfm?pageid=4088, accessed May 21, 2009.

[14] "National Aquatics Center, Beijing (The Water Cube): Award for APM Project Management Awards 2008."

[15] "Total Design," Arup, internal document, 2008.

[16] This section draws on "National Aquatics Center, Beijing (The Water Cube): Award for APM Project Management Awards 2008."