Multidisciplinary Practice and Engineering Innovation

The Opera House and the Watercube

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***Abstract*—**The imperative of multidisciplinary practice has been identified as one of the effective ways to make technological innovation. The main incentives underlying are limitation of disciplinary knowledge, increasing challenges in the constantly changing market, and changing of traditional working flows. Multidisciplinary practice forms collaborative environments and encouraged interactive design activities between practitioners with varying knowledge backgrounds. It helps the establishment of social nexus, encouraging creativity and technological innovation. The consequence of multidisciplinary practice provides an opportunity to re-shape the mode of practice, to re-distribute power relationships between people, to re-allocate financial benefits, even to transcend the profession towards a cross-boundary paradigm.

Through the comparison the Sydney Opera House and the Watercube Beijing, this paper reviews the difference between two traditional cooperation and multidisciplinary collaboration, and argues how multidisciplinary practices encourage technological innovation in the profession.

***Keywords*—**Comparative study, Collaboration, Multidisciplinary practice, Engineer innovation.

I. Introduction And Incentives

SINCE the twenty-first century, more and more innovative buildings have been raised, such as the Watercube in Beijing, which was designed by multidisciplinary team. In the building industry, the mode of multidisciplinary teamwork is not a recent phenomenon, but has some new features under the changing socio-economic context since the new millennium (2000). The main incentives of multidisciplinary practice are limitation of disciplinary knowledge, intensive competition in contemporary profession, and the young generation's [1] ambition to change the traditional working flows.

The limitation of disciplinary knowledge links with disciplinarity. The concept 'disciplinarity' involves a mechanism in education, accreditation, in the profession. Although the institutionalisation of disciplines and the inter-subjective character of disciplinary norms make disciplines resistant to alteration, disciplines nevertheless grow and evolve[2]. In other words, these knowledge-based disciplines are dynamic rather than static. Sometimes definition of discipline is based on criteria for validating a particular intellectual community in terms of subject, methodology, curriculum and purpose. However, such divisions raised new problems in practices. For example, practitioners in the architectural profession, such as architects, sometimes faced unprecedented problems that seem to render traditional disciplines unresponsive, and in such circumstance the definition of architectural discipline will be admitted to under strain. In addition, everyone has the limitation in knowledge and every discipline has it limitation as well. Therefore, the possible solution to overcome the strain of disciplinarity is to transcend traditional disciplinary methods, discourses and ideas into an "all-in-one" unity is 'collaboration'—through a multidisciplinary teamwork.

Intensive competition in a globalising scale requires constant adaptation to the shifting market, somehow because that demands in the building market are decreasing. Failing to fulfill the formidable requirements of potential challenges from architecture, technology, environment and arts, may result in the loss of company's competitive capacity. Although some large firms, such as the Arup, have more variety of opportunities than small firms, their capacities are all constrained by personal or institutional factors. Nowadays, all kinds of firms need to consider about 'capacity and ability' for competition, and each firm has its advantages in respect to its unique expertise; however, it would need to access other companies' resources to enhance the quality of their works. When each firm offers specialist, unique expertise, new technology to other collaborators, an equally collaborative relationships could be able to be established, the chance of making innovation beyond architecture is increased[3].

Many practitioners criticized on the traditional hierarchical structure in the architectural profession, and their experiences shows the restriction of innovation is due to the old

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[1] This refers to people born after 70s, such as the Generation X, Y, Z, see: http://www.socialmarketing.org/newsletter/features/generation3.htm.

[2] Robert Post. "Debating Disciplinarily. *"Critical Inquiry,* Vol 35, No. 4, The Fate of Disciplines, Edited by James Chandler and Arnold I. Davidson (Summer 2009): 749-770.

[3] Margaret A. Somerville, David J. Rapport eds. "Transdisciplinarity," McGill-Queen's University Press (December 9, 2002).

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mechanism[4]. This has called an advanced mechanism in the profession.

II. Collaboration: from Multidiscipline to Cross-discipline

Collaboration can be understood as a framework of horizontal integration where a number of companies operate in related activities establishing joint agreement for knowledge, technology and information exchange, which entails new creative knowledge and opportunities to make innovation. The initiative to collaboration is a 'reciprocal' opportunities and relevant benefit, regardless the scale of the firm and its background. In other words, each participant in a collaborative team is aware of the opportunity and the need for external inputs. The intellectual agenda of multidisciplinary collaboration is based on collective intelligence rather than individual wisdom, and collaborative teams also create opportunities of raising capital or generate cash flow to smaller companies. Some of these teams worked together for short or medium term, focusing on one specific project[5], and based on traditional structure—architect as the team leader, (such as the Sydney Opera House); while others worked together with equally shared positions, which is known as a strategic partnership in the length of collaboration and allocation of resources (such as the collaborative team of the Beijing Watercube—including Arup, CCDI, PTW and etc.).

Indeed, collaboration has had a long history in both architectural and engineering practices, but it retains in the process of transition under various contexts. For example, the works of the Sydney Opera House project had been spanned more than one decade, wherein fulfilled by interactions and interventions between experts, disciplines, as well as some governmental organisations. It reflects particularly on how the multidisciplinary team facilitated technology innovation in the 60-70s, whereby tough challenges of the shells and the glass walls had been successfully resolved based on 60s and 70s technology. However, the contemporary profession, (here refer to the time after 2000) has shown new features in terms of multidisciplinary practice, such as Jones[6] claimed that the new mode of collaboration not only been altered, re-organised, but also been transcended to a higher integration that incorporating alternative sub-disciplines and new relationships between each other, such as features that have been reflected from the collaborative works in the design process of the Watercube Beijing.

III. Objective

This paper claims how multidisciplinary interactions facilitate collaborative environments for architectural practices; therefore encourage innovation in engineering innovation. It depicts two types of collaboration trajectories through the comparative study of the Sydney Opera House and the Watercube Beijing, and revealed the changing spectrum of multidisciplinary collaboration ranges from traditional design coordination to cross-disciplinary practice.

IV. The comparative approach

The comparative method embodies the logic of comparison in that it implies that we could identify and analyse underlying changes, identical features and distinction when they are compared in relation to two cases—the Sydney Opera House and the Watercube Beijing. Normally the levels of observation could include individual level, group level, or organization level; for this study, the primary unit of observation and analysis for the comparative study is on the organizations level, focusing on interactions between different companies and people from varying disciplines. In other words, this research draws on observation of organizations, such as the changing organisational structure in the process of development—from hierarchical to equally shared positions, or to some other alternatives; and interrelations between architects, engineers and other practitioners,

The Sydney Opera House is a selected example to illustrate the interactive process of multidisciplinary practice before 2000, which provides evidence of multidisciplinary interaction in the late 60s. It is one of manifestation of historical origin dealing with complicated issues through multidisciplinary team works in the process of design, and the Opera House project made unprecedented innovation in its age. The Watercube was designed for the 2008 Beijing Olympic Games, via international competition selection. However, the realization of the innovative structure and material is due to a collaborative teamwork rather than designed by architects only. Therefore, it has also marked a new milestone due to its structural innovation and the unique collaborative practice.

V. The sydney Opera house

The realisation of the Sydney Opera House (1957-1973), comprises not only Jørn Utzon seminal works, but also a numbers of collaborators' contribution that derived from a long course of exchanging knowledge and multidisciplinary practices, in order to make optimised decision to enables novel solutions. There were two primary teams involved—Utzon's team and Ove Arup's team, who had been maintaining constantly interactions in the course of developing the design of the shells and the glass walls[7]. The challenges of free-form shells that came from the competition motivated the designers to create something new to comply with Utzon's novel imagination at the stage of further design development without any existing references, as neither architects nor engineers cannot handle the challenges by themselves; they had to rely on each other, and pushing forward the scheme together accompanying with critique on proposals, revise procedure, and revised again. The Utzon's team, the Ove Arup's team and relevant governmental organizations, together with three technical advisory panels (Professor Ashworth for the

[4] This is a summary from a number of interviews I have done, based on interviewees' opinion.

[5] Helen Lawton Smith, Keith Dickson, Stephen Lloyd Smith. "There are two sides to every story: innovation and collaboration within networks of large and small firms." *Research Policy*, 20 (1991): 457-468.

[6] Jones R.A.P (1997a) Forward. *Holistic Nursing Practice*, 11(3), vi-vii.

[7] This can be referred to Watson Anne's unpublished doctoral thesis, *Chapter 8 'Contentious corners,' the challenge of the glass wall*, Faculty of Architecture, Building and Planning, University of Sydney, Australia.

architectural design and construction; Haviland for traffic, and Heize for Music Drama[8]), had all been worked on how to deal with the technological challenges of the Opera House since 1957. Compared with other projects that have been designed by Jørn Utzon, the new question need to be explored, for this stage of teamwork of the Opera House, is to identify the engineering innovation was made by whom (individual or group)?

Fig. 1 The Opera House[9]

The engineering innovation included a package of features of creation of feasible geometries for the 'shells,' which are the output that has experienced revolutionary transition—design, calculation, structural formulation, and so on. The transition of these shells is pre-eminently expressed in the expanded collaborative relationships that have been response to cross-boundary practices, collective intelligence, and new rise of technological empowerment. In this sense, Arup seems contributed more than the architects at this design stage. On the ARUP side, specialists including Ronald Jenkins and Hugo Mollman, who had been involved the design of the shells, and worked as 'design engineer' rather than 'structural engineer' or 'technology engineer'. The architectural team that involved in the shells included Utzon, his disciples who were working in Utzon's atelier, and some other architects, such as Rafael Moneo. In the course of design, the positions of these specialists were dynamic; and the inter-firm interactions had been well maintained. The team also formulated a role as "design engineering", who was active in both architecture and structural engineering. One reason for the Arup to obtain the empowerment from the architect, and took some responsibility to make technological innovation was 'Working in the office had a timeless quality about it; Utzon was continually investigating new solutions but, with a reluctance to commit himself, he would worry away at a problem for months.[10]' The mode of their practice denotes an approach that has developed new models for structural design of geometric complexity that challenged orthodox methods of structural engineering.

In retrospect, the first scheme of the shells was conceived by Jørn Utzon based on his hand drawing in 1957, a competition-winning scheme, which articulate sculpture quality of its profile and silhouettes (See Figure 2, the 1957 part). The second step was that Arup created a geometric discipline, adopting a system of parabolas for the shells, a proposition as close as they were able to fulfill Utzon's free-flowing shapes and allow the Arup team to start accurate calculations of the stresses and loads. In 1958, Arup developed both parabolas and ellipsoid proposals to Utzon and did initial structure tests, confirmed two specific features: the geometry was based on either parabolic or ellipsoidal geometry; the open end of the shells were closed off with "Louvre[11]" walls and the two halls were each one continue structure, the shells interlinked at their springing points[12]. These features indeed had been changed after Utzon expressed he disliked the solution, and combined with the fact that the model tests showed unacceptable high forces near the ground. Then Jenkins produced a scheme that could stand up, but Utzon rejected it; Jenkins was understandably frustrated, and this resulted in the withdraw of Jenkins and the resign of Molman from Arup[13].

The Arup then decided a new team and to apply new approach—to develop the double-skin scheme, which was Arup's commitment to meeting the architect's aspirations that tested the engineers' skills to the limit. Jack Zunz took the responsibility at the critical moment, and the new engineer team separated the three sets of shells from each other. The double skin was essentially a steel structure with internal and external surfaces (See figure 2 the part from 1959 to 1961, that shows the section of the double-skin plan).

In August 1961, Utzon articulated his discontent to Arup as: "I do not care what it costs, I do not care what scandal it cause, I do not care how long it takes, but that is what I want," which drove the Arup following a series of discussion about the problems of constructing the ribs with both the circular arc rib scheme and the ellipsoid scheme. After one month, Utzon announced that: "I have solved it." He has created the shell geometry from a single sphere, based on which Arup had achieved a resolution finally following Utzon's ideas. The side effect for this was it is apparently that the silhouette had been radically changed; the smooth-curving shells of the competition entry had been exchanged for the upright arches of the spherical solution. Toward the end of 1961, Utzon is quoted as saying: " We will not be able to separate structure from architecture when it has been finished," which summarised the inter-connections of the architects and the engineers. From 1962 to 1963, (See Figure 3, the 1962-63 part), underwent the scrutiny from the government, the Arup, the solution of shells had finally determined.

The next saga is to deal with the challenge of the glass walls. This stage includes a number of practitioners involved, such as Jørn Utzon, Peter Hall, John Nutt, Croft and Hooper, Yuzo Mikami, Ted farmer, etc. The resolution of glass walls of the Opera House experienced a tortuous route, which began with the final scheme of Jørn Utzon in1965. In Utzon's final scheme, he offered a plywood mullions' proposition, which required durability tests that was seemingly time consumption to the engineering team of the Arup. While an onsite meeting in 1967

[8] Peter Murray. The saga of Sydney opera House. (New York, 2004).

[9] The photo was taken by myself.

[10] Peter Murray. *The saga of Sydney opera House*. (New York, 2004), 24.

[11] This part of transition, please see the glass wall part, page 11.

[12] Peter Murray. *The saga of Sydney opera House*. (New York, 2004).

[13] This can be referred to Watson Anne's unpublished doctoral thesis, *Chapter 8 'Contentious corners,' the challenge of the glass wall*, Faculty of Architecture, Building and Planning, University of Sydney, Australia.

had decided to continuously develop the concrete and bronze-clad mullions scheme rather than to conduct the durability tests for plywood mullions, as Arup were considering alternative solutions. The reason for this was Vilhelm Jordan, who worked in the Arup London office, examined some of the acoustic features of the material to be used, and the continuation of the bronze cladding on the mullions around the building, presumably at this stage might be a 'visual necessity.' On the tenth of August, Yozu Mikami wrote to Hall after he returned to Sydney, setting out the philosophy for the glass walls agreed to the London discussion, which balanced the disconnection between Arup London office and Arup Sydney office. In February 1968, the scheme was announced in Hall Todd & Littlemore's first published set of drawings for stage three, the so-called 'White Book.' It was however, not the end, it went through another two years before the scheme approached resolution.

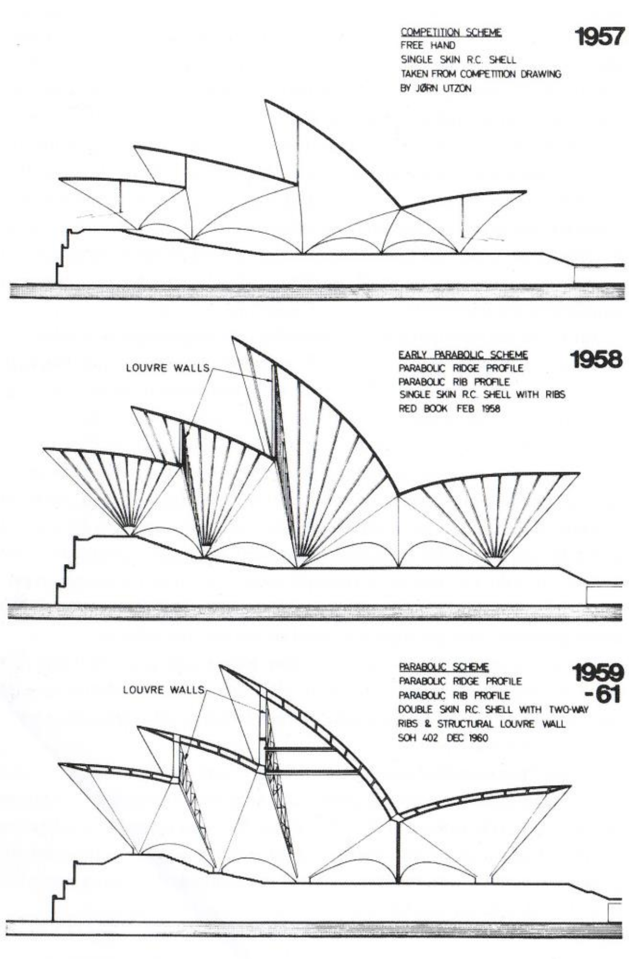

Fig. 2 The transition of the shells (1957-1961)[14]

In the late 1968, *Architecture in Australia* published its progress report—the 1968 'Estimate for Ultimate Development', in which noted that the architects had to date explored many schemes for the glass walls, and the solutions to the seemingly unending problems of the glass walls increasingly taxed the close collaboration and coordination between architect and engineer. In the early 1969, the development of the glass walls confronted a critical point, as 'many complex conditions to satisfy' in order to complete the walls: the shape need to fulfill the requirement of providing circulation spaces; the design of supporting structure that allowed the walls to appear to 'hanging from the shells.' In the meanwhile, it seemed that the collaborative team required to solve all remaining hurdles, where an 'intensive technical development program' was essential[15].

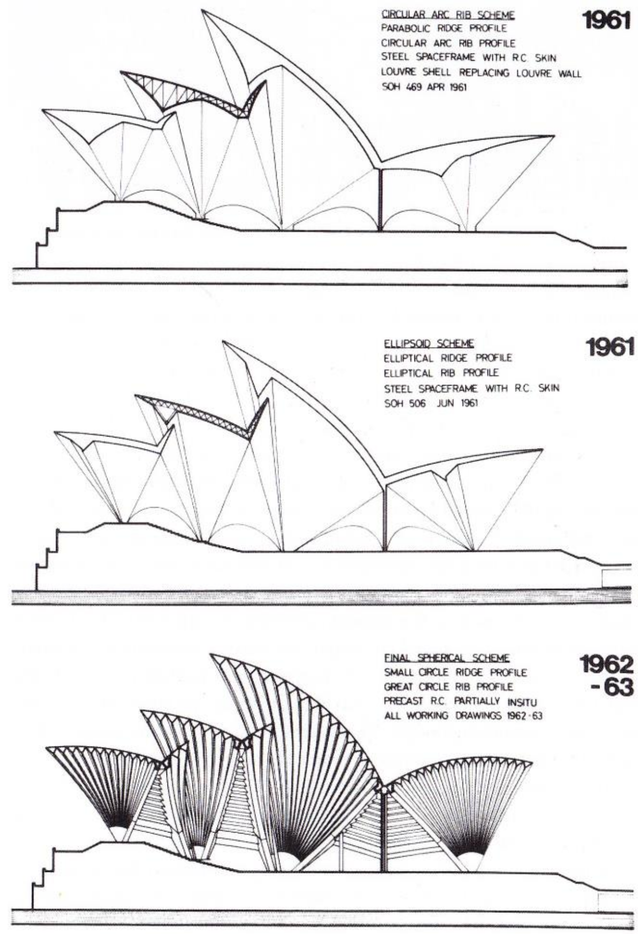

Fig. 3 The transition of the shells (1961-1963)16

The complicated evolution of the north glass wall design from the middle of 1969 to its final iteration in the early 1970s, was merely documented in State Records files and drawings. Despite the best intentions of the 'team structure,' the cooperative working relationships between the architects and the engineers had run into a dilemma. The problem was the engineers' insistence on the need for a defining geometrical principle for all the glazing, which would enable it to be mathematically modeled and hence capable of analysis by computer. While for the architects, the imposition of an overall geometry was too restrictive and aesthetically undesirable, particular in the treatment of the eastern and western ends of walls. By March in 1970, the scheme of the glass walls had achieved a consensus view finally—to adopt steel mullions

[14] Peter Murray. *The saga of Sydney opera House*. (New York, 2004), 24.

[15] Lionel Todd to Project Officer, PWD, 17 March 1969. (SRNSW4/8051.1)

[16] *Ibid.*

rather than the plywood mullions, and the first glass walls' construction began in 1971 (See Figure 4 The interactions).

From these two sagas—the shells' sage and the glass walls' saga, the traditional chain of working flow of the architects and the engineers, which are based on a hierarchical sequence had been altered to a shared model, to a certain extent, i.e. the engineers shared some of the priority from the architects. Therefore, 'structural engineers' took up a range of challenges such as handling design responsibilities, or incorporating new technology, and acted as a 'technological-designer' throughout the process of design. This shared process could transcend the information and knowledge coming from different professionals into an integrated entity, which cannot be separated by pre-defined boundaries of disciplines.

Although the structure of the multidisciplinary design team of the Opera House was not a complete model of equally shared structure, despite the seemingly equal interactions between different practitioners; it made great improvement compared with the traditional modes from the one direction chain towards an multiple interactive mode. For example, in the phase of design the glass walls, the materials, the technologies and the constructing approach that finally adopted were based collective agreement, and have been comprehensively described by various authors, such as by Peter Hall, John Nutt, Croft and Hooper, and by Yuzo Mikami, Ted farmer, etc. The saga of the glass walls shown that technological difficulties were more possibly to be solved, when architect and engineer allied at the last stage and intellectually support each other.

Sydney Opera House Glass Wall

	Time	People or Team	Development	Description	Connection
1	1965	Utzon	Final Scheme	Plywood mullions	Utzon's Legacy
		Hall Todd & Littlelmore	On-site meeting	The concret and bronze-clad mullions scheme continued to be developed	The design philosophy and geometry still adhered to Utzon's legacy scheme.
2	1967	Arup	Meeting	Consider some alternative solutions	The alteration began
3	Aug-67	Yuzo Mikami	Wrote to Peter Hall	Set out the philosophy for the glass walls, and outlined the basis for the redesign of the walls. Ted Farmer, attended the Sydney meeting, recommend the continuation of the concrete mullion scheme.	The first round amendment of Utzon's legacy
4	1968	Hall Todd & Littlelmore, Arup	Team meeting	Published a set of drawings for stage three "White Book," described briefly about a new elliptical cylinder geometry dictating a system of parallel steel mullions.	Responds to Utzon's 1962-65 glazing scheme—first 'Yellow Book' design
5	1969	Hall Todd & Littlelmore	Reported the critical point	There were many complex conditions to complete the glass walls	A collective process required to solve all hurdles
6	1969-1970	All team members	Worked together	Architects, engineers worked together, following opposite ways, employing compromise to each other, and achieved the consensus—steel mullions and glazing bars.	The collaboration that led to technological innovation began.
7	1970	Arup	Discussed the 'contentious corners'	Kelman, Yuzo Mikami, Peter Hall all believd it remained controversial.	All challenges were resolved by collective works.

Fig. 4 The glass walls of Sydney Opera House—Interactions

VI. The Watercube

However, compared with the Sydney Opera House, the trajectory of the Beijing Watercube (also known as the National Aquatics Centre) entails innovation within multiple design companies, who worked under a trans-cultural environment. The multidisciplinary design team composed of the PTW, engineers of Arup, and CCDI, who had successfully managed to succeed in the design competition. The Watercube Project was built to host the swimming and diving events for the 2008 Summer Olympic Games in Beijing, and the selection procedure was through an international competition. The concept is to dematerialise the building, and to capture the spirit of water. Based on this concept, the collaborative team create a building not only embodies elusive features of water and bubbles, but also integrated skin, structure, and performance requirements together. The material of the skin had been decided to use ETFE (ethylene tetrafluoroethylene), which is more appropriate for such function than glass, as it is strong and resistant to fire, earthquake, thermal efficiency, energy saving, heating and cooling, degradation from ultraviolet light and air pollution.

Fig. 5 The Watercube17

The initial conceptual scheme of the Watercube had been changed dramatically from a wave-shape scheme, which was proposed by the PTW architects, to a cube. The scheme and design for the building was developed in Australia, and the project was then handed over to a team in Beijing (in CCDI) who develop documentation for the Watercube. Disciplines involved in the design process include not only architecture, engineering, but also physics, mathematics, computer science and environmental sciences, and not limit to these.

The multidisciplinary team intended to create a feasible structural system and ETFE enclosure with the close expression to bubbles from water. They did some experiments on soap bubbles, and done some research on the theory of Irish physicists Denis Weaire and Robert Phelan[18]. The question for the structural system was how to divide space into an equal number of free-form organic cells with the least surface areas between each other, like 'foam.' Designers then faced a new challenge—to generate a constructive structure from the theoretical 'bubbles' structure. In the course of solving this issue, the Arup played crucial role[19], and conquered this challenge finally, as it is the Arup announced that they had successfully make the bobble-like structural system into a feasible steel structural system, which was tested in computer calculations. The final structure was determined as honeycomb like formation, which was based on Weaire and Phelan's 'foam' is made up of a combination of polyhedral with twelve to fourteen faces each. Tristram Carfrae, the leader of the team in Arup, who worked in the Arup London office described as: " When viewed at an arbitrary angle, it appears totally random

[17] http://www.meiguoxing.com/images/National_Aquatics_Centre_-_The_Water_Cube_-_night_view_blue.jpg

[18] In 1993, the Irish physicists Denis Weaire and Robert Phelan provide a solution to that was called Kelvin problem (named after late 19th century British mathematician William Thomson Kelvin).

[19] 'Inside Beijing's Big Box of Blue Bubbles,' *Architectural Record*, v196, Issue 7, 2008.

and organic." The division of cells shows the successful integration of multidisciplinary knowledge, including architecture, structural, physics, mathematics, material, and computer technology[20]. The final scheme embody the concept of water, the values and aspirations of China, testing materials, and expressing form in the most dynamic way.

The next agenda was to fit pillows into the steel structure. The first issue is how to make the 'pillows' to fit in the structure. The team split into groups to workshop design principles, calculation, environmental factors and structural concepts for the issue to be quickly identified a ranged of possible arrangements for the façade design. Arup was in charge of the material's ability for fire safety, earthquake and weather adaption. The CCDI took the task to array these pillows into the frame, from wrote a script to assemble an infinite array of the Weair-Phelan units, rotated it in three dimensions, and them sliced the packed cells to create a box 584 fee square in plan and 102 feet tall. They created a pace frame by replace the edged of the polyhedral with steel tubes that meet at spherical nodes, and then decided to encapsulate the space frame in 4000 'bubbles,' air-filled ETFE pillows to fabricate a vented cavity 12 feet wide within the walls and 25 feet deep within the roof, protecting the steel structure from the corrosive humidity of the pool environment[21].

The design process is hereby a hybrid process. The documentation of the Watercube's structural system is the output of sophisticated analysis and optimized software that Arup invented specifically for this project, which helped examine the space frame under various loading scenarios to determine the scale, shape, weight and other properties for steel tubes. All these characteristics were recorded in database for the formulation of three-dimensional models, which in turn used to produce the construction documents. Chris Bosse, a former project architect at the PTW and now the director of the LAVA, stated that: "there is a lot of talk about auto-generated architecture, but this (the Watercube) was one of the first projects where such a process was realised." On account of the high degree of automation that the parametric process afforded, the team could generate a complete set of new construction documents in less than a week, which is amazing in terms of both the speed and the quality[22]. The process of fabrication of the ETFE pillows depended heavily on digital technology, but sometimes the data required some manipulation, when to address some parts of the skin where the 'bubbles' were interrupted. Finally, the ETFE 'pillows' had been installed by the Vector Foiltec, with the collaboration of a local manufacturer, which marked an innovative milestone for aquatic architecture.

VII. Multidisciplinarity And Innovation

From the review of multidisciplinary practices' features of the Sydney Opera House and the Beijing Watercube, we can find both identical features and distinctions. The invaluable factor that ensures both the Opera House and the Watercube to achieve the optimised outcomes, is the value of the collaborative team and the successful implementation of multidisciplinary practice; the architects and the engineers had therefore established a 'collaborative environment', which provide a hybrid integration for the project to be cultivated, transcended and innovated. On the discipline aspect, the collaborative witnessed the process of new disciplines and sub-disciplines emerged, altered, replaced, and how the alterations contribute to the making of technological innovation. On the knowledge aspect, the allied design firms, such as Arup and Utzon's team, PTW, and so on, combined multidisciplinary creative capacities, integrating the diverse knowledge sets and skills needed together, and achieved innovation that fulfill the technological rationality, architectural functions, and structural aesthetics.

For the Sydney Opera House, the characteristics of the multidisciplinary collaboration are: (1) Utzon worked as the chief architect has proposed the scheme first, and then the interactions occurred after a pre-existing proposition; (2) Although Arup made the technological innovation was partly due to the pushing from the architects, after Arup took the 'technological designer' responsibility, the relationship between Arup and Utzon had actually altered towards a more equal trend. (3) The answer of 'who did the design' do not has definite answers, because the design process was conducted by collective team rather than an individual, so it is difficult to identify an individual contribution under such context. Indeed, it is contribution of the alliance rather than one company. "It was Arup's commitment to meeting the architect's aspirations that tested the engineers' skills to the limit,[23]" as "Utzon had certainly solved many of the difficulties of constructing the shells by his conversion to spherical geometry—but it was a conversion that took place after months of discussion with engineers[24]."

Whereas the Watercube project has some exclusive features: (1) Arup has involved into the initial conceptual design, the final scheme was not followed that engineers followed the architects' ideas, but architect and engineer worked together, generating the idea together, and developed it into a feasible scheme. (2) Rather than 'pushing' from the architects, the Arup took a more important role in the project of the Watercube, which changed its imbalanced relationship more than that happened during the Opera House, with the architects, technologist, and so on.

Through the comparison of these two multidisciplinary practices, where different firms and technological institutes cooperated and collaborated, and then they had successfully conquered a number of unprecedented challenges that one party could not able to achieve, and prompt the efficiency of technological 'innovation,' by announcing new formulation of landmark architecture, as well as contribute to each firm's reputation and competitiveness. Such practices have profound influence on creativity and technological innovation. Creativity has been conceptualised as: (1) the individual personality traits that facilitate the generation of new ideas, (2) the process of

[20] *Watercube, The book*, Baraona Pohl, dpr editorial, 2008.
[21] 'Inside Beijing's Big Box of Blue Bubbles,' *Architectural Record*, v196, Issue 7, 2008.
[22] The information was from the talk of Tristram Carfrae, leader of the multidisciplinary team, working in the Arup London office.
[23] Peter Murray. The saga of Sydney opera House. (New York, 2004), 31.
[24] *Ibid*. 35.

generating new ideas by teams, (3) outcomes of creative processes, and environments conductive to new ideas and behaviours.[25] While innovation is associated with purposeful change; an attitude reflecting the capacity to imagine what does not exist or a process of different stages extending from an idea to its implementation[26]. Therefore, creativity is identifies with ideas generation, while innovation implies ideas transformation into new products or service. In this sense, creativity is part of the innovative process, and they both could be achieved by multidisciplinary practice. Multidisciplinary teams establish 'collaborative environments,' which supplement inter-company's capacity and played an important role in ideas generation and new architectural innovation. Firms are able to develop new technologies to gain competitive advantages, such as the Arup adopted specific software for the calculation of shells, and new documentation system for the structure of the Watercube. Last but not the least, a common goal of all allied firms is the incentive for idea generation, which help to focus on development the initial concept and making innovative objective. The collaborative design is a process of how challenges were identified; idea evaluated; mistakes handled; changed strategy; communication supported, etc.

This paper identifies conditions of multidisciplinary practices in the process of making engineering innovation, and illuminates the interactive processes in the Opera House project and the Watercube project under various contexts. The two cases show how a series of coherent developments in the face of difficult challenge had been formed into agreed consensus, and then put into implementation. The trajectories of these two cases, leading from competition scheme to the final implementation, show that multidisciplinary teams provided practitioners with the competency of coherence, complementarity and competitiveness, which led to innovative outcome in terms of quality and creativity. These activities are particularly innovative when firms could establish competitiveness upon new building those cross-disciplinary boundaries.

In conclusion, different forms of multidisciplinary collaboration provide a good framework or an active platform for technological innovation to occur or encouraged in the making of novel architecture. In the architectural profession, for both architects, engineers, and other practitioners, in the future, the trend of multidisciplinary teamwork could become a new paradigm due to its innovative substance and advantages. However, the implications of multidisciplinary practice are not that one needs simply reduce an emphasis on individual creation and replace it with collective innovation, but that the teams which composed of members from different companies, need ongoing development to enable a blend of individual and group innovation.

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