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A Case Study in Complex Concrete Construction in Australia: A Hybrid Approach of Hand and Machine

Chris Knapp
Abedian School of Architecture, Bond University, Gold Coast, Robina QLD 4226, Queensland, Australia

Abstract: This paper describes and provides a critique of the design and implementation of the "scoops"—a set of bespoke multifunctioning architectural free-form elements that are a highlight of the new Soheil Abedian School of Architecture at Bond University, Australia, by the office of Sir Peter Cook and Gavin Robotham, CRAB (Cook Robotham Architecture Bureau, London). The development includes the transfer of analogue design processes into digital 3d modeling, which is then analyzed and rationalized via an exchange with consultants and procurement contractors. The complexity of the concrete works necessitated the use of digital fabrication to make their implementation affordable and within time constraints, with said complexity creating a variety of challenges for many aspects of the entire delivery team. The 3d model played a critical role in communicating intent and accuracy at all stages. The use of site-based craftsmanship combined with computer aided design and fabrication overlapped to realize the project.

Key words: Concrete construction, design and implementation, modeling.

1. Introduction

Architects and designers work in an age today where achieving formal complexity in their work is readily achievable via the spectrum of software platforms and modeling processes one can access in the studio environment. However, taking complex formal qualities into the built world within budgetary constraints and quality standards is still often an experimental process and one imbued with risk. Pushing experimental work forward is critical for the discipline to advance [1], and through these instances, the procurement process is seen to evolve into more integrative means of collaboration and production between all parties in the building process [2]. Modeling software which allows transference of information between disciplines—particularly across the chasm that often exists between parties focused upon design and those carrying out implementation—is a key in enabling the integration required for novel and progressive advances in our spatial and material environment.

In December 2010, the office of Sir Peter Cook and Gavin Robotham, Cook Robotham Architecture Bureau Ltd (CRAB Studio, London) won a two-stage, open competition to build a new faculty of architecture at Bond University, Gold Coast, Queensland, Australia. The newest building on a campus originally designed by Arata Isozaki, the Soheil Abedian School of Architecture is a predominantly concrete building with bespoke glazing infill and a lightweight steel roof that will house 250 students upon completion in mid-2013, within a net area of 2,500 m^2.

The building is a culmination of Cook and Robotham's experience as both architects and as teachers at leading institutions globally. Informed by this academic tenure, the project incorporates responses to many anecdotal criteria that are particular to architecture schools, as well as constructional and climatic objectives. The sociology of intimate groups within institutions, the value of casual overlay, and the importance of the non-curricula moments are all embedded in the project.[1] The primary physical embodiment of this attitude is

Corresponding author: Chris Knapp, professor, research fields: architecture, design, digital fabrication.

[1] http://www.crab-studio.com/bond-university/ (07-02-2013).

featured in what is also of the most compelling aspects of the project: several four-story tall in-situ concrete elements referred to by the designers as "scoops".

Carrying out a variety of programmatic roles, the "scoops" support the roof, act as a buttress for lateral loads, accommodate vertical circulation along their perimeters, function as ventilation chimneys, create a venue for design critiques, and also carry light down into the central recesses of the building (Fig. 1).

Adding to this complexity is the formal resolution of the "scoops" themselves. These elements are customized in each instance although they share a common spatial and material quality in their totemic placement within the project's organization. The "scoops" curve in plan, splay in multiple directions in section, are punctuated with multiple voids and structural connections, and in two instances, support cantilevered concrete stairways (Fig. 2).

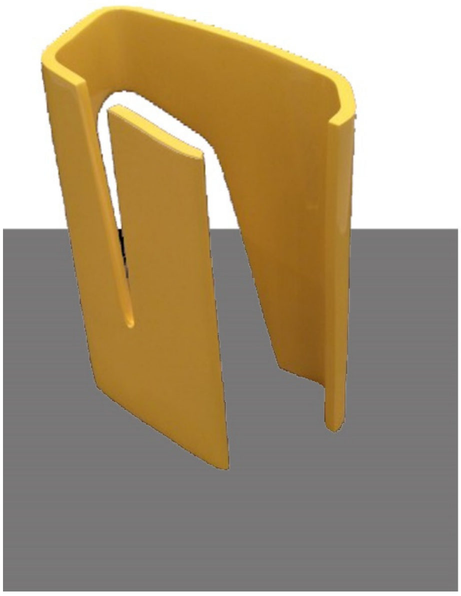


Fig. 1 Scoop conceptual model and study drawing (CRAB).

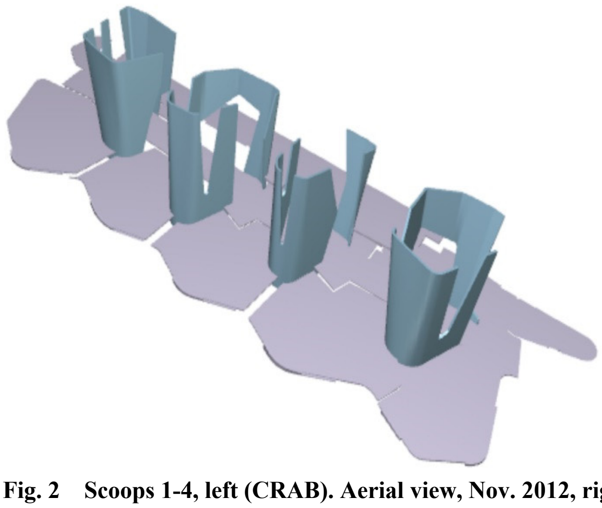
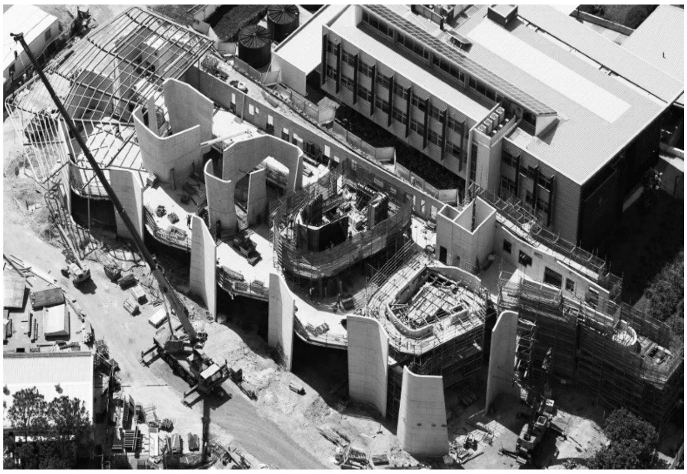

Fig. 2 Scoops 1-4, left (CRAB). Aerial view, Nov. 2012, right (ADCO).

2. Design Process: Competition Stage

As is typical of Peter Cook's work, the project was initially developed using heuristic methods of sketching and physical modeling to develop and test the radical formal qualities of the project [3] and then was quickly developed through the use of McNeel Rhinoceros 3d (Rhino) and subsequently documented with Autodesk AutoCAD to hit immediate targets for stage 1 of the competition phase. Conceptually, the "scoops" played a prominent role in how the project was conceived and represented in the early-stage development of the project. Sketches by CRAB director Gavin Robotham indicate the interdependence of the "scoops" to anchor the scheme and Peter Cook's "cartoons" for the competition presentation cast the scoops as the backdrop for key narrative scenarios in the building (Figs. 3 and 4).

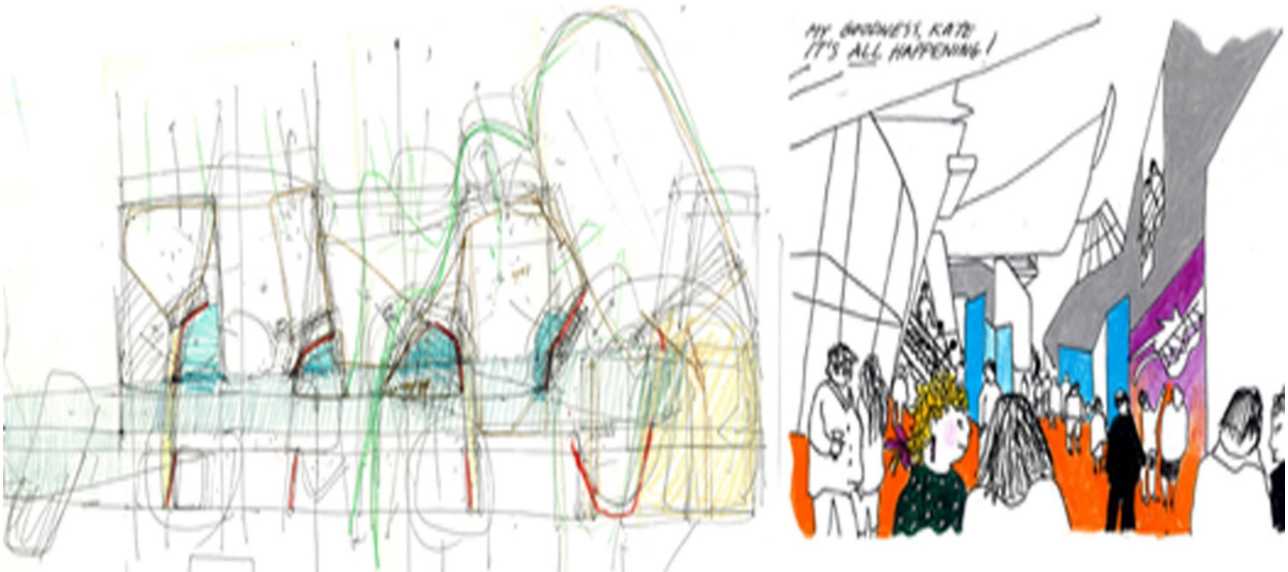

Fig. 3 Sketches of the project showing scoop conception. Plan by Gavin Robotham (left), and Perspective by Peter Cook (right) (CRAB Studio).

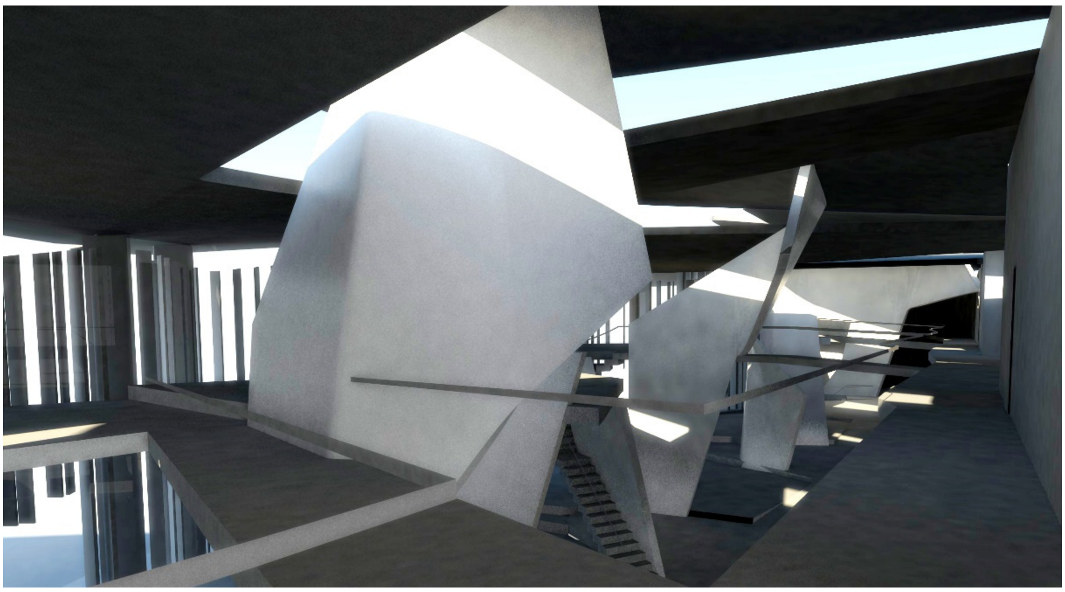

Fig. 4 Competition image of "scoops" at mezzanine level (CRAB Studio).

Upon being shortlisted and then winning the competition, one can see early evolution of the "scoops" takes place into articulate elements, as CRAB necessarily began to shape the project toward realization and an appropriate balance of complexity tempered by the client's project budget of approximately $15M AUD through adjustments within the Rhino environment.

3. Design Process: Development and Validation Stage

As noted, the entire building was designed in the CRAB office in Rhino. Rhino was used to create a multitude of instances and virtual prototypes of the scoops in the context of the overall design, as well as to generate physical laser-cut and 3d printed study models. Beyond the office, the Rhino model proved to become an essential element of the procurement documentation.

To implement the "scoops" and other in-situ concrete elements of the building (including doubly-curved shear walls in the building envelope), the Rhino geometry was then passed on to ARUP Brisbane as a DWG (drawing) file in conjunction with PDF (portable document format) drawings. Similar to the process of engaging Bernhard Franken for the Kunsthaus Graz as noted by Kloft [4], the structural engineering phase did not put any design pressure on the project and was able to support the designer's intent fully, as the "scoops" are effectively normative load-bearing structures despite their geometric complexity. A principal challenge from a structural point of view was the accessibility of vibration equipment into the curving forms amongst the required density of reinforcing steel.

4. Implementation Process

The true complexities and challenges inherent in the concrete work required for the project became recognizable to the construction team only after the project works commenced. The project was carried out on a design/build contract per special arrangement between the client and general contractor to allow for very specific control over the value engineering process. As such, the contractor controlled and distributed all documentation, including the 3d model which was generally used by the contractor and sub-contractors in the form of a 3d PDF for ease of distribution. In the first instance of developing the cost plan, CRAB's 3d model, drawings, and the structural engineering documentation were transferred to concrete subcontractors for tendering and a contract awarded to a small but relatively experienced and regionally-based concreter. CRAB Studio had conceived that the concrete work would be cast using custom-made steel formwork. However because very little of the geometry allowed for more than one pour, the contractor proposed site built plywood forms used in conjunction with limited re-usable formwork as the basis of their methodology, but within the first week of construction it was clear the complexity of the works would cause significant obstacles to achieve the necessary accuracy using conventional means of site carpentry. The contractor contacted international formwork supplier, PERI, to provide a possible solution. PERI Germany has previously implemented complex freeform geometry on the Mercedes Benz Museum, Stuttgart by UN Studio (parts of which were enabled by the consultancy designtoproduction[2]) and also two projects by Santiago Calatrava, among others.

The 3d model proved to be the essential basis for communication of the exact intent and dimensionality of the desired building. Development of the formwork shop drawings was undertaken at PERI Germany in AutoCAD 3d and then transferred to PERI Brisbane for implementation locally, using the Rhinoceros model as the key reference document to achieve conformance to the required configuration.

5. Revised Process

PERI proposed a process used on previous freeform projects, namely, a system of "waffle slab" or notched

[2] http://www.designtoproduction.ch/content/view/15/28/ (07-02-2013).

plywood formwork with a curved skin. This method, akin to developing cross-sectional prototypes, allows for the creation of curved and raking surfaces on the pour side of the form, while maintaining a plumb and level face on the opposite side to which wailers, bracing, and buttressing can be affixed during the pouring process. The notches in each perpendicular plywood rib enable site carpenters to easily and quickly jig the forms together with precision.

Due to the nature of the geometry in the first instance of the design, the PERI cost estimates for this method initially came in very high, due to the quantity of plywood required and the number of customized forms. At this stage, CRAB revisited the scoop geometry to introduce a greater degree of inter-changeability in the formwork geometry. This was handled rather intelligently to still achieve diversity and variation in the outcome, particularly by setting like formwork at different base angles in different scoops, for example (Fig. 5). One strict limitation of the formwork was the need to keep the outside face of the modules plumb, allowing the implementation team to verify accuracy in the form setup. However, this limited the degree of further efficiencies in the re-usability of the forms, as a CRAB strategy was simply to tilt the "scoop" geometry from one to the next. Because of the vertical face parameter, the "scoops" necessarily required more unique formwork to achieve the desired diversity of formal outcomes.

Following on from this process, the project was re-evaluated by PERI and found to achieve the necessary cost reductions and thus a new strategy fixed into place for procurement of the "scoops". Each "scoop" in the project required 4 to 5 pours or lifts from top to bottom, with the average height between pours being 3.3 m. In total, approximately 400 separate forms had to be installed for all 4 of the "scoops", with just under 50% of those forms being re-usable. As such, the customisation, tracking, and integration of the formwork needed to be highly detailed and organised. The forms themselves were fabricated from 18 mm plywood and then surfaced with successive layers of 6 mm or 12 mm plywood coated with polyurethane to achieve the required class 1 finish.

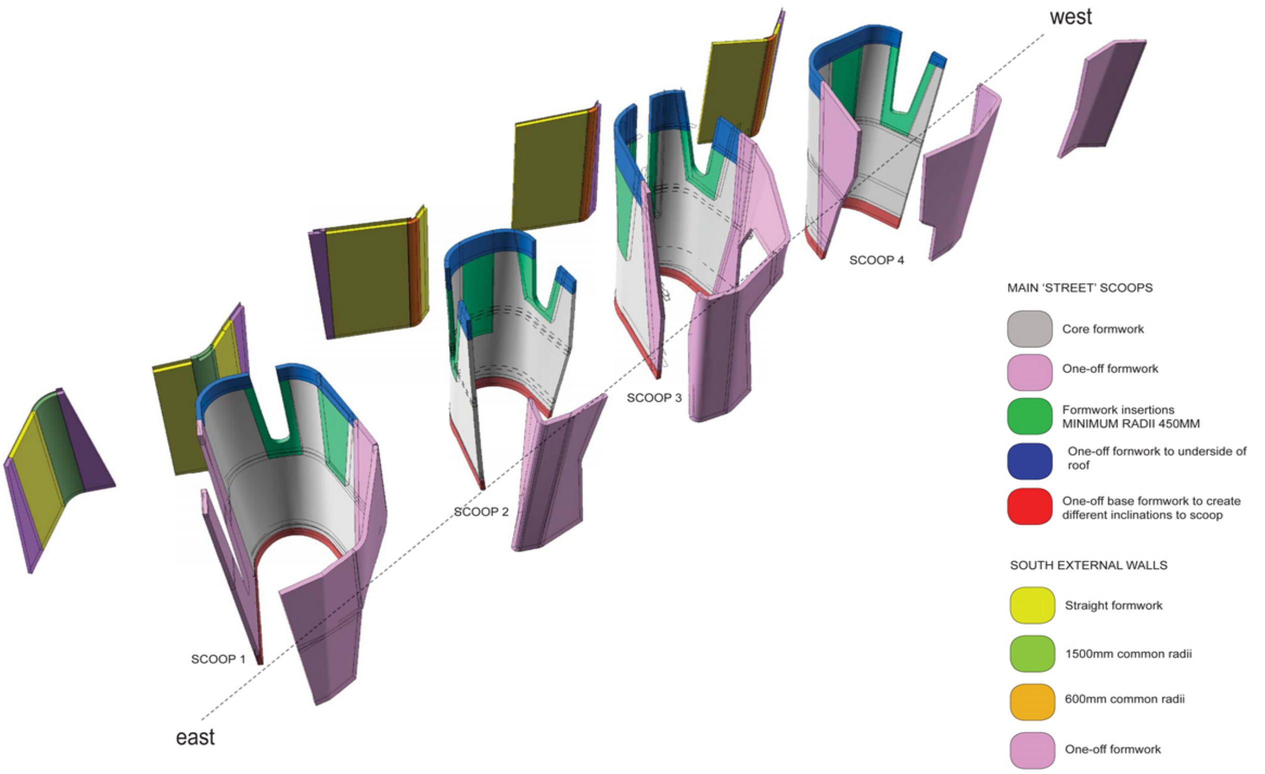

Fig. 5 Scoop rationalisation of formwork (CRAB).

PERI Germany developed the formwork shop drawings using AutoCAD 3d from CRAB's DWG file export. A manual technique requiring hundreds of instances of Boolean intersections to find the necessary curve geometry was undertaken, and from there, the ensuing drawings developed much like a drafting exercise as opposed to one of modeling. The need to establish a parametric model in this case, while perhaps obvious in retrospect, was not developed. Reasons for this are further elaborated upon in the concluding remarks, but it is important to point out the limited ability for collaboration to ensue between parties because of the construction contract. Adding greater constraint to the process, CRAB specified precise layouts for expressed form joints and tie rods, which were articulated in unrolled representations of the scoop geometry (Fig. 6). Further reconfiguration was required to ensure as many full sheets of plywood, thusly minimizing the number of joints.

Next in the process, PERI Germany sent two sets of files to the Brisbane office for issue to the concrete contractor. These included PDF A1 format shop drawings detailing every element of custom formwork (again, more than 400 drawings, or approximately 100 per "scoop") and also a DWG file describing the waffle slab form as an un-nested, un-labeled 3d model view (Fig. 7). The concrete contractor was responsible for unrolling and flattening all of the cut file geometry in AutoCAD and supplying it to the CNC fabrication subcontractor who then nested it, cut it, and sent it to site for assembly. This entire process of sorting the digital model was performed manually by CAD draftsmen for 2,400 plywood sheets (Fig. 8).

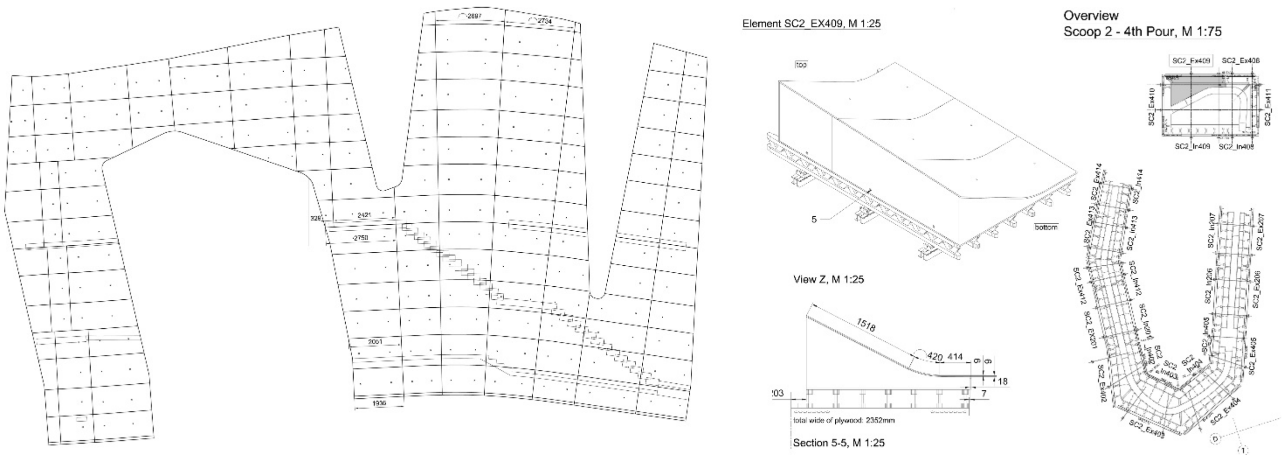

Fig. 6 **Unrolled scoop elevation (left), and formwork shop drawing detail (right) (PERI).**

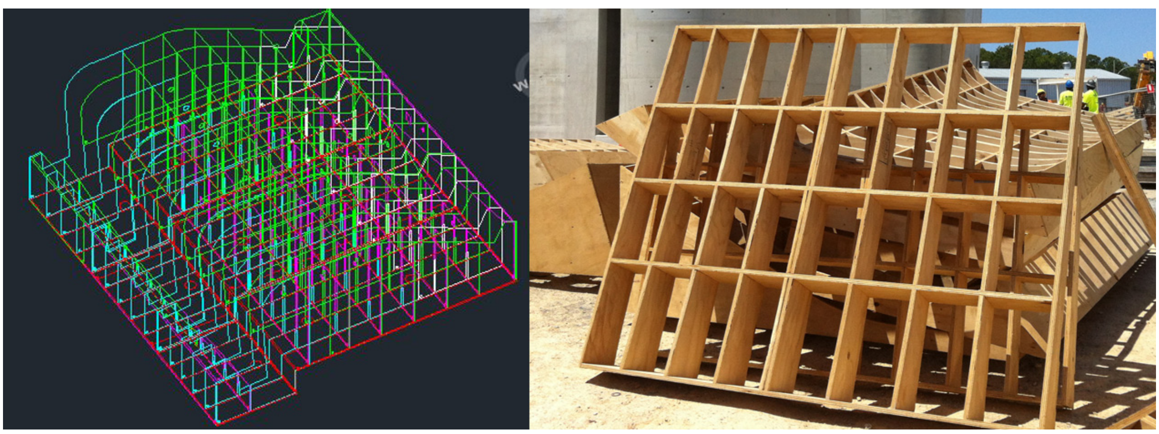

Fig. 7 **3d formwork shop drawing model (PERI) (left) and formwork frame (right) (photo by author).**

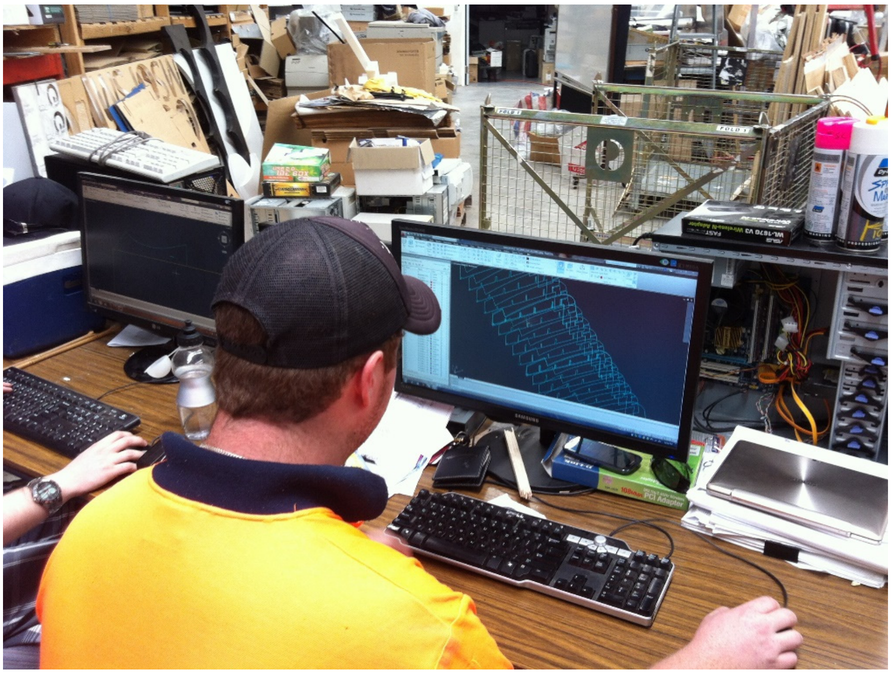

Fig. 8 A draftsman, employed by the concrete subcontractor, manually un-nesting formwork ribs for CNC cutting (photo by author).

6. Challenges and Results

A team of 35 formwork carpenters and laborers was required for on-site construction of the "scoops" and other concrete elements, in addition to those in the stages of design and prefabrication. While the concrete was greatly aided by the supply of two-way gridded plywood formwork that was inherently self-jigging, many challenges still remained. Issues such as the varying radii, which required surfacing the formwork with different thicknesses of plywood in-situ, were one such challenge. Additionally, the PERI formwork indicated the location of tie-rods (or "Z-bars") but the CNC milled formwork did not accommodate this in a conflict-free manner. Again, a more sophisticated approach to move between modeling, planning, and fabrication, would have helped to alleviate such conflicts. Furthermore, the contingencies of on-site construction led to marginal but significant errors. Slight irregularities in the footings, for example, led to formwork being out of plumb, and thusly resulted in inaccurate connections and the next lift if they were not identified prior to the pour. Figs. 9 and 10 show a typical view of the construction site and illustrate the extreme lean and splay of the "scoop" formal qualities.

A surveying team assisted to verify location of the formwork before all pours, and also to create as-built reference points after each pour to prepare for the next lift. The surveyor relied exclusively upon the CRAB 3d model, and similarly, subsequent trades in steel and glazing required these as-built drawings for their shop fabrication.

The engineering of the "scoops" required N-12 reinforcing steel at nominal 150 mm and 300 mm centres, encased by 40 MPa concrete with 10 mm aggregate and 100 mm slump to ensure it wet enough to conform to the geometry without leaving voids or deformities. With all care taken, many irregularities, such as lipping or small voids, did however eventuate and grinding/patching was required extensively. Furthermore, the interchange of plywood form surfaces mixed with proprietary steel forms where they were able to be used, meant a large range of resulting surface qualities that required mitigation.

At the inception, the concrete work was anticipated to unfold over a 6-month period. Instead, the works lasted nearly 12 months. While the prefabricated forms

Fig. 9 Construction process on site—assembly area for formwork (photo by author).

Fig. 10 Construction process on site (photo by author).

Fig. 11 "Scoops" nearing completion prior to roof placement (photos by author).

ameliorated the complexity of the project, the nature of the project was inherently difficult. While the building team proved up for the challenge, it was also a process that was entirely novel for most involved, and thusly proved to be a very slow process and one which was very costly, but in the end very successful given the overall quality of the work and powerful formal qualities of the architecture.

7. Conclusion

The conception and implementation of the complex concrete work in the form of the "scoops" at the Soheil Abedian School of Architecture represent a hybrid formation of both analogue and digital methodology, and offer a demonstration, in the finished product, of how these overlapping approaches integrate successfully (Fig. 11). The Rhino model developed by CRAB was not only used for the structural form of the building, but also used to design and manage the development of finer levels of details, from stairs to handrails to joinery. As a carefully controlled experiment, the team members involved were forced to innovate with the available digital tools and analogue methods available, and as previously suggested, one can identify areas in which the process could be improved or enhanced.

Compared to precedents for concrete construction in Australia, of which the Sydney Opera House is perhaps the only iconic peer, the work described here exceeded the experience of all members of the building team and required a tremendous leap in their pursuit of the required product. While PERI had previous off-shore experience with developing the requisite sophisticated formwork via CAD/CAM technology, the information flow was constrained, with no mechanism for feedback from the carpentry team to influence subsequent rounds in the process. As such, the handcraft aspect of the process played an important role in closing the gap at the end of the digital workflow. Works of greater formal complexity such as in Toyo Ito's work at Fukuoka Island Park or Kakamigahara Crematorium [5] demonstrate similar difficulties resolved by modeling, digital fabrication, and site-intensive craftsmanship, but it is worth pointing out even in these instances the concrete work was poured as open face slabs, not cast between formwork which increases the complexity dramatically.

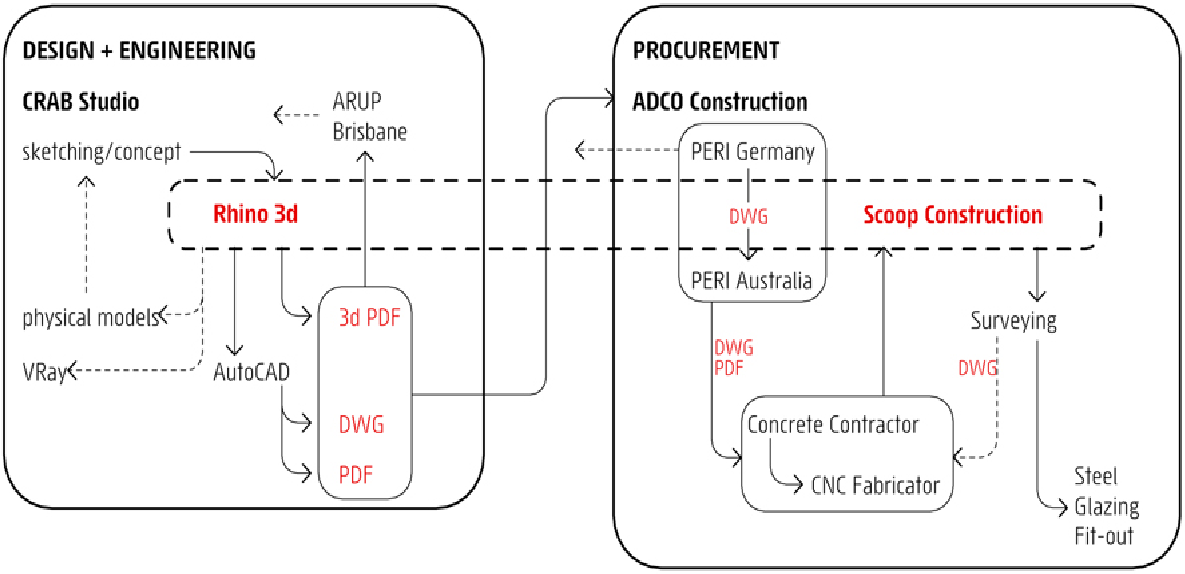

Fig. 12 Workflow emanating from CRAB 3d model (by author).

Regarding information flow, this project offered a prime opportunity to apply an integrated project delivery method, and similarly, the appropriate technological platform to support it. The standard design/build contract creates a segregated process, inherently bisecting the workflow into a "before and after" sequence relative to awarding the tender as indicated by the two main boxes segregating the parties in Fig. 12. Projects such as this with elevated levels of complexity require the input and feedback loop between the builder and designer to allow for refinements and sharing of expertise. The Australian "Alliance" contract or the North American "Integrated Project Delivery" would allow just the type of non-standard protocol required [6]. Even through the Rhino model allowed for information flow and for CRAB to maintain review of conflicts between the model and the as-built condition, the contractual apparatus inhibits this review. Furthermore, while CRAB made a very determined effort to share their specific intent with the Rhino model and corresponding DWG shared file, the platform does not support dynamic collaboration as would BIM platforms, such as Digital Project [7]. Alternatively, one can also look to specific formwork plug-ins being developed for Rhino that would enable the designer to play a more central role in the process [6] without relying upon BIM tools.

The formwork engineering and fabrication could have been improved and streamlined, but again this is most likely, for this project, the best result and process that was able to be implemented given the sum total of all constraints and levels of experience. The manual process of developing section profiles, labeling and nesting, of the individual plywood forms is a process which, using Grasshopper for example, could have been automated and compressed tremendously. Furthermore, this plug-in for Rhino would have easily integrated with CRAB's preferred platform and allowed for parametric updating of all 2,400 cut files at the stage when the scoop geometry was rationalized. In this way, CRAB could have occupied a central role and thusly greater collaboration with the actual scoop construction, offering an example of architect-as-master of this digital-craft intensive process [8]. The contractual apparatus applied to the project inhibited CRAB's ability to communicate effectively once such problems and opportunities were identified post-contract. Alternatively, the engagement by the contractor of suitably experienced and skilled consultant could have aided the process by providing parametric maintenance of documentation. Few consultancies, such as designtoproduction in Europe or CASE in New York, presently exist globally but they represent an emerging and important professional model for the architectural discipline. In Australia, the firm AR-MA (Sydney) represents one such entity that could have provided the required digital facilitation to the general contractor within the confines of the traditional building contract employed here.

An exemplary outcome in complex concrete construction that all members of the process are rightfully proud of, the "scoops" and other concrete works at the Soheil Abedian School of Architecture provide a valuable example of progress in the capacity of the Australian construction industry. The assessment and objective review of this process can hopefully serve to inform future endeavors of similar or advanced complexity, which for the professional design disciplines is an imperative for growth. This project signals the need for tighter collaboration, effective contractual integration of team members, and perhaps most significantly, the need for appropriate digital technology to support efficacious delivery in a dynamic construction process with complex formal and spatial objectives.

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