Structural shop drawings at the Sydney Opera House: An instructive model of information flow?

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Abstract. The history of the design decisions directly related to the construction of the Sydney Opera House remains largely anecdotal. A rich group of items recently discovered in Australia may now start filling this gap, as documents brought to light include the drawings issued by the general contractor to build the concrete formwork for the shells, drawings of the temporary structures and falsework, site images, and contractor's notes. All in all, the drawings display sophisticated combinatory solutions for attaining the structural form required whilst introducing repetition and flexibility in the making of the discrete pieces. While suggesting a remarkable combination of manufacturing and structural shrewdness, these blueprints call into question the canonical history of the building roof's famous 'sails', the rhetoric of the 'spherical solution' used to arrive at them, and, most importantly, the information production and knowledge management model we conventionally work within.

1. Introduction – Shop drawings and their currency

Contrary to conventional perceptions, modern buildings are only partially built out of professional designers' drawings. For the most part, the instructions these embed are transferred onto ulterior representations produced by industry suppliers and work contractors, the goal of which is to interpret design consultants' ambitions and translate them into fabrication and erection routines. The development of a building is in fact the result of the progressive exchange and integration of a number of descriptions within the social space of the 'project'. Amongst these descriptions are shop drawings, non-contract 'production' documents that describe the manufacturing process leading to the realization of the building. Shop drawings must conform to design concepts, but are specifically prepared by contractors to illustrate how they will execute their portions of work. Their purpose and representational focus is different from that of contract drawings. While the latter define how project components must be at the conclusion of the operations, shop drawings reflect the various phases of these components' transformations by trades, thus providing critical information on how building parts are progressively assembled off- and on-site [1] [2] [3].

Contemporary building historians such as Johnston [4] [5] and Gundersen McBride [6] have written on the significance of shop drawings' role in marking the industrialization of building activities from the XIX to the XX century, and in signalling the separation of professional design from construction planning and components' manufacturing. Even a traditional architectural historian like Summerson has paid oblique reference to their importance in understanding the evolution of building production in the Victorian world [7]. In general, however, their generation and content have not featured prominently in the design theory debate, perhaps with the exception of scholarship focusing on design and engineering challenges that required manufacturing and construction process innovation. Indeed, the building work of engineers such as Pier Luigi Nervi (1891-1979), Pietro Belluschi (1899-1994) and Eladio Dieste (1917-2000), or that of a contractor such as Rafael Guastavino (1842-1908), need shop drawings to be fully explained in its material inventiveness [8] [9] [10] [11] [12].

In contrast to their limited presence in traditional design discourse, shop drawings have started to appear consistently in the technical discussion on the organization of information in the building process at least since the 1960s, first with the studies on communication in construction and modelling of construction activities – such as those by Ward [13], Bishop and Alsop [14], Honey [15] and Turin [16], and then with the studies on the changing divisions of labour in building design – for example Gray and Flanagan [17] [18], Bennett and Ferry [19], Haviland [20], and, particularly, Pietroforte [21] [22] [23], Notably, these later studies remark on the growth of shop drawings in relation to other types of project-based documents. More and more, decisions about manufacturing and construction at project level are taken on the basis of visual information produced by the building side of the process. Indeed, it is the relationship between these documents and the responsibilities of professional designers that has generated attention from law circles and professional institutes, due to the significant legal repercussions of shop drawings' review and approval by architects and engineers [24] [25] [26] [27] [28].

The situation has become more sensitive in today's project environments, due to the digitalization of design and project management activities. While exploiting the rhetoric of architects as new master builders on the architecture side (see, for example, Marble [29], or Overall et [30]), and streamlining efficiency on the construction side [31] [32], building information modelling (BIM) platforms open to iterative contributions from all parties are blurring the distinction between professional and non-professional inputs to the building project [33].

If they are part of the same integrated model, how can one distinguish their function and the responsibility of those who made the decisions embedded in them? How can one recognise and trust expertise?

2. The terms of the problem

Paradoxically, the current problem is not one of information transfer, since its logistics have mostly been resolved. Rather, it resides in the new-found pervasiveness of shop drawings, and one's ability to decipher the technical and semantic connotations of the information exchanged across the team, which can reflect designers' project ambitions (construction documents), contractors' industrial strategies (shop drawings), or a synthesis of both [34]. Digital technological evolution, in other words, requires a sharpening of document production theory more than the acritical acceptance of document transfer practices [35]. The sharpening of document production theory, of course, demands attention to the content embedded in and transferred through the drawing, as well as the relevant actor's ability to produce it. From this perspective, the analysis of shop drawings could also be interpreted as an indirect evaluation not only of their producers' competence in representing and organising their specialised knowledge, but also of their capacity in responding strategically to a given project challenge by laying out production routines that speak, as well, of their own industrial ecology. This double bind project-industry confers shop drawings (both historically and currently) an unusual context-clarifying ability, because – by-and-large – the procedural aspects they contain cannot be totally invented; they must reflect a cargo of adaptable experience and operative reflection. They imply prior practice. Thus, information-rich shop drawings suggest a mature industry, capable to suit specific professional instructions whilst responding to its own autonomous product assembly logics.

However, if the above statement depicts an optimal stage of development, it says nothing about its progression dynamics. In fact, how an industry, and the shop drawings reflecting its practices, learn is an important topic in the context of information production and knowledge management studies in building. Do building construction and innovation rest on ad-hoc manufacturing capacity, or does manufacturing evolution require building opportunities?

3. Enter the Sydney Opera House

A project like the Sydney Opera House (1958-1973), celebrating the fiftieth anniversary of its opening next year, epitomizes the difficulty of answering such a chicken-and-egg question. Is it an endeavour made possible by its professional conceivers – architect Jørn Utzon's and engineer Ove Arup's teams – or was it critically facilitated by the industrial context in which it was raised?

Architectural history has by-and-large privileged the first thesis, and assigned the project team a legendary status in the production and resolution of challenges, thus privileging histories of individual success and agency over histories of collective engagement and anonymous authorship [36] [37]. This has somehow inhibited interest in the broader vision of the project as a major industrial event and its eventual connections with local building activity. But what if one looked at the building from the side of construction and the practices of the contractors involved? Would this perspective change our understanding of its history and the society that built it? And could this perspective unfold by using the technical drawing argument as an analytical scaffold?

This is what the authors believed to be the case when launching into a search for the drawings produced to construct the building [38] [39]. Originally, it was the problem of the actual fabrication of the roof sails of the Sydney Opera House, a topic widely debated yet never scholarly addressed in construction detail, which had triggered the applicants' interest in searching across various archives in Australia and overseas for the technical documents enabling their planning and erection. The authors' experience in the analysis of construction processes was suggesting that the documentation produced by the general contractor for the task should have been copious and highly prescriptive or propositional, thus generating a more-than-anecdotal window on the project's complexity as well as on the contractor's capability to deal with it. A very recent publication by John Kuner, Raising the Sails - The story behind the building of the Sydney Opera House roof [40], confirmed both the formidable challenges embedded in the endeavour and the importance of studying it from a construction perspective. Yet it also confirmed the absence of technical supporting documents, as the book was almost entirely produced from participants' own testimonies, photographs and sketches. Proper recording and evaluation of the product engineering part was still missing

4. Missing project records to the rescue

A rich group of items produced by Hornibrook, the general contractor for Stage 2 of the building (1962-67), and recently discovered by the authors in several locations across the Australian state of New South Wales, may now be set to shed important documentary light on the details of the work and the collaborations it entailed. The documents include site notes, new original site images, and a massive corpus of 5,300 drawings issued by the contractor, including construction layouts of the site as well as calculations and execution instructions of the temporary structures used for the erection of the building roof's famous 'sails'. Though technically classifiable as shop drawings, i.e., non-contract production documents describing the manufacturing process leading to the realization of the building, Hornibrook's sets betray strong degrees of design integration with the drawings produced by the structural engineer ARUP, which, in several cases, contain explicit references to 'Hornibrook solutions'. If this type of notational citations suggests at least an accredited combination of efforts in the project, scope and magnitude of the shop drawing series reveal the considerable endeavour of the construction company in the conceptual ordering of the physical tasks. Among the collection of drawings, 85 of them describe the formwork system developed to build the concrete shells. Examining this lot is interesting because it reveals not only the length of the engineering work on the contractor's side but also the integration of industrial fabrication thinking and ad-hoc construction concerns (see Figure 1 below).

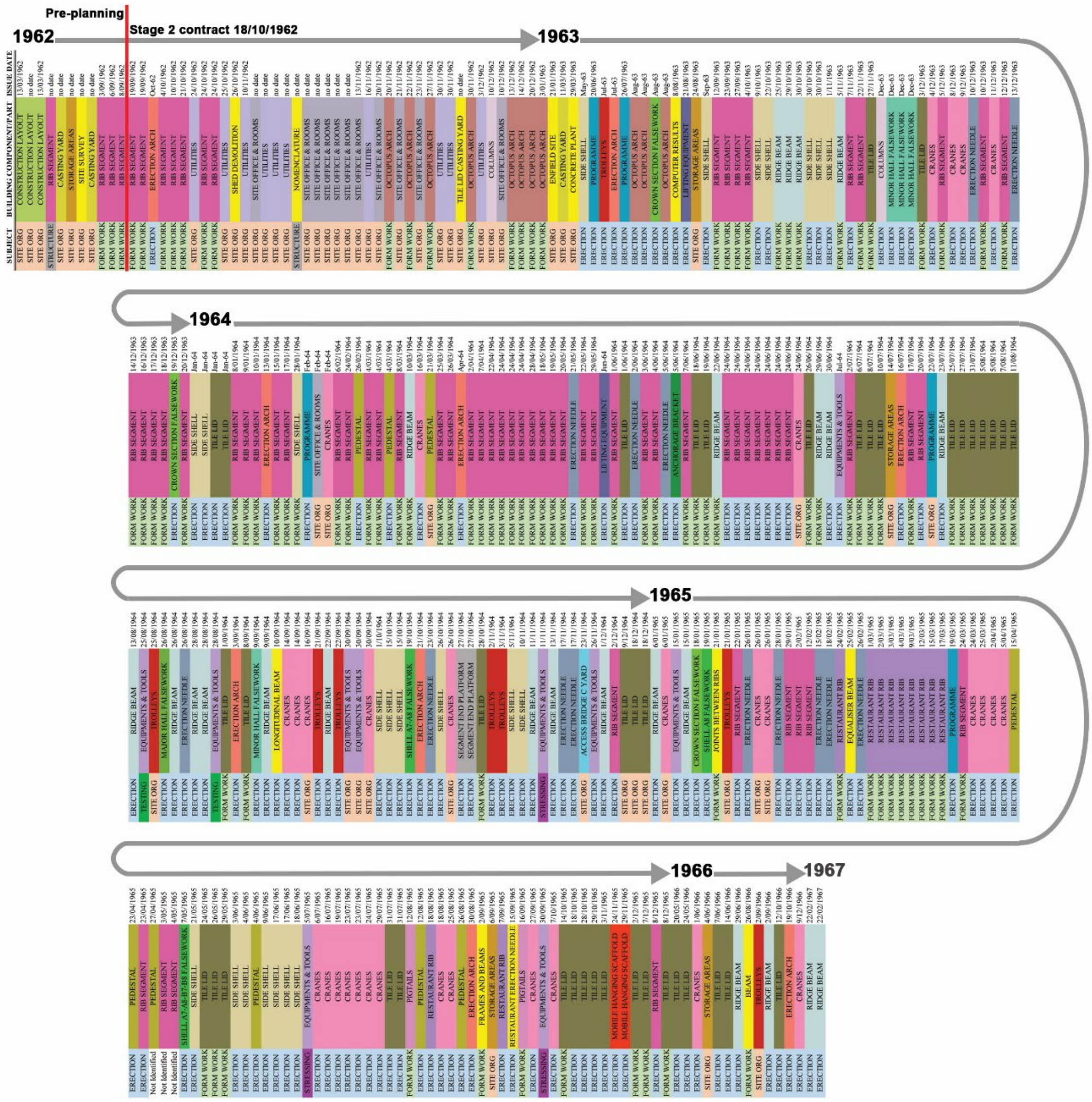

Figure 1. Sydney Opera House, Stage 2 (roof construction), Shop Drawings Analysis. This analysis shows Hornibrook's production flow of shop drawings for falseworks, erection procedures, mechanisms, formwork systems and site organisation.

5. Drawing the construction of the roof

To understand the achievements, one must first introduce the problem, which in this case concerns the roof of the Sydney Opera House and the form of its main components, also known as the 'sails'. These have been described as a combination of 'side' and 'main' shells, with the latter taking the shape of an ogive vault formed by a series of arches labelled 'ribs'. The dominant geometry describing each half vault is a slice of a sphere with a radius of 75 meters, which gives all the ribs the same curvature and allows them to be notionally divided in concentric and repetitive segments. Each rib is formed by a variable number of segments with a Y-shaped cross section. All ribs start with three solid concrete segments, followed by a fourth one featuring a cylindrical void to reduce its weight, and the remaining ones designed as an open Y, closed at its top by means of precast cross bracings. Moreover, as each half vault feature a fanlike spherical shape all the ribs have a tapering section that increases from bottom (pedestal) to top (ridge). Mutual connection between segments of the same rib was assured by a stabilizing compression force obtained with prestressing cables running along the rib's radius. As such, the result post-tensioning forces were 'nearly centroidal' with each rib being self-supporting upon its completion. Each ogive arch or rib is completed with a special last segment acting as a connector between the rib and the ridge. Like the ribs, also the ridge of the vault is formed by a series of concentric precast elements. Leaving instrumentally aside all the cast-in situ elements of the system (i.e., pedestal and tripods footings) and its special pieces (i.e., ridges, crowns and warped segments) allows one to focus on the formwork designed and tested by Hornibrook for the production of the rib segments. As explained in the drawings, each formwork accommodated five contiguous segments. Each segment was separated by a precast bulkhead which, besides working as a formwork diaphragm, also acted as a matrix for the positioning of the spigots and the anchor plates that had to be embedded in each segment. Moreover, to assure the necessary geometrical continuity between segments, the segment last poured in the previous formwork was positioned as first in the following one.

Formworks were made out of two moulds: an exterior one and an inner one. The form of the exterior one was shaped against the Y cross-section of the ribs. It was divided in two shells that could be closed and opened via a rail sliding system actioned by hydraulic cylinders placed at the base of the shells. The shells, built with a light frame structure in steel studs and plywood lining, were completed with a cast-in-situ curved spine, running along the centre-line of the rib that realized the base form of the Y stem. Once the formwork was stripped from the segment, the central spine acted as temporary support for the piece itself before it got lifted by the crane. For the fabrication of the steel inner forms, Hornibrook designed a special timber jig with two adjustable horizontal arms through which it was possible to set out the interior tapering geometry of each segment, necessary to follow the varying cross section resulting from the discretization of the sphere in slices. Once realized, the inner form needed to be adjusted and modified so as to allow the insertion of pockets and corbels for stressing anchors, bolts and other permanent connections. Original shop drawings show a series of so called "modification to inside formwork" alternatives, which illustrate and detail the numerous construction variations required or imagined.

In synthesis, the drawings for the formwork articulate sets of sophisticated combinatory solutions for attaining the structural form required whilst introducing repetition and flexibility in the manufacturing of the discrete pieces. In order to do so, their producers had to consider the vertical layering of segment sub-pieces across the Y section of the rib as well as the tapered progression of the segments along the curve of the half arch, which was made possible by the introduction of sliding registers into the idea of the form. All this without losing sight of the limited, narrow space available to organise a casting yard around the footprint of the building, in itself demanding a high rate of reuse of the moulds, as well as stockage locations for the segments awaiting erection. Shape, length and functioning of the formwork, in other words, had to respond to architectural ambitions, structural engineering requirements, manufacturing precision and speed, site logistics, and economy of materials.

Such challenges acquire significance against the celebrated 'spherical solution' for the roof, namely the breakdown (or approximation) of the original roof shells into triangular sectors belonging to the same sphere, which is by now part of architecture's modern history [41]. On the one hand, the 'spherical solution' allowed for a conceptual macro-discretization of the sails into ribs, and for envisioning the production of the latter through a nearly industrial process. On the other hand, at the 'segment' scale, it could not foresee and solve all the engineering issues embedded in the very solution, which remained open for the construction of a roof constituted by over 2,400 precast segments, the majority of which required an ad hoc precast bulkhead, precast cross bracing, and specific adjustments to accommodate all the necessary post-tensioning apparatuses.

To get a proper gauge of how construction requirements affected each of the segments in relation to their position, the authors devised a map of each segment contributing to the main sails. Such a map permitted to establish the number of variations occurring for each segment. If one looked at one of the two main shells as a whole, for example, this counted 169 segments, with features that changed 49 times. Utzon's virtual grid was formed, in theory, by a series of identical parts, or segments; in reality, it gave rise to a complex ribcage formed by a series of quasi-identical segments, which required the structural engineer ARUP to issue 30,000 dimensions to Hornibrook – dimensions that were promptly translated by the contractor into detail drawings often supplemented with data tables indicating variables dimensions and locations of single details [42]. Those dimensions were generated by a system of coordinates based on the spherical configuration which was also at the base of the surveying criteria adopted for controlling both the casting yard (including the formworks) and the erection of the roof.

6. Contractor's design agency

Even such a short analysis of the construction of the formworks for the structural segments of the sails enables a series of considerations on the work conducted as well as the process that led to it. Firstly, it shows the enormous amount of product engineering and operational planning that went into the definition of the catalogue of components and their casting procedures. Whilst responding to the building performance requirements set by the architect and the engineer, the general contractor made strategic decisions concerning sub-component geometries and combinations, moulding systems and fabrication sequences, element re-use patterns and bespoke requirements. Type and extent of the documentation produced, together with the photographic records of the operations on site, betray the significant degree of autonomy enjoyed and exploited to this end. While the geometry of the precast components of the arches suggests differences with the streamlined aesthetics of the architectural surface of the sails, it does respond very well to both the production-related needs for modular yet flexible casting on a difficult site and the extreme complexity embedded in the task of recomposing all the pieces of the tri-dimensional structural puzzle. Hornibrook's successful search for manufacturing efficiency and assembly viability suggests that the elements of interest in the construction of the sails go beyond the definition of their overall form and the methods employed to extrude its surface in layers. Indeed, they include the composition of its discrete precast pieces and the process of manufacturing them. This because it was the set of decisions underpinning such a process that determined not only the layout and the organization of the site but also structured construction operations and quality assurance methods for critical parts of the project and important portions of its duration. The casting of the formworks thus bears testimony to the existence of 'agency' functions on the general contractor's side, requiring vision and the ability to enforce it. As an inevitable aside, due to space limitations of this paper, it could be important to reflect on the fact that, if Hornibrook's experience and track record to this point of its history had produced a kind of manufacturing shrewdness capable to respond to the challenges thrown at them by the official professional design team, the company's actual ability to do so on the Sydney Opera House was determined contractually, by the provisions explicitly regulating work boundaries and expectations of the builder during Stage 2.

Irrespective of the importance of contracts in enabling critical contributions to project developments, did the work of Hornibrook as described amount to 'design', or did it embody the mere translation of design intent into instructions for production, as per the conventionally accepted nature of shop drawings? If one looked at the image of the building and the compositional logics of its structural system as a whole, then the answer to the design question would be negative. By servicing a higher order concept - that of the form and the structure of the sails - the contractor's documentation and the work instructed within it would be subordinate to these main ends; as such, they would not constitute design per se. Yet, if one considered design almost etymologically - as "a problem-defining, problem-solving, information-structuring activity that, on the basis of understood conditions and rules, defined specific courses of action" - then the casting of the formworks would attain full design status. In fact, when sketched in these terms, design activity would not be limited to what definable solely under architecture prescriptions or structural engineering work, but rather enter all the specific dimensions of the building procurement process - including at least site layout, building components production, building erection, and building use and maintenance. Such scenario would shape the idea of both 'building' and 'project' in scholarly useful ways, with 'building' becoming understood as the combined result of the implementation of multiple scope-specific designs; and 'project' indicating the social space where the gradual integration of these designs would occur, following a process of negotiation between objectives internal to each design dimension and objectives related to their integration - very much the case with the work carried out by Hornibrook on the Sydney Opera House.

7. Design as a broad construct to manage

Opening the notion of design up in the way just outlined makes it plausible to turn established mental images of construction around and think of the building process, with all its ramifications, as a system of design production independent of corporative schemata - a cycle, that is, within which all the information necessary for the implementation of the building would have to be conceived and either produced or assembled. How this system organized to deliver its product, what logics it followed in doing it, what it would be constrained by, and how many units of production it would consist of would then become the object of the discussion. Such a conceptual framework would add critical dimensions to the analysis of the design process and its dynamics, certainly by positing the importance of socio-technical diversity within the project team, and with it the relevance of sophisticated actor-networks descriptions across the history of the project. Analytically, the design system of sorts determined through this exercise would be helpful for two reasons. Firstly, because it would provide a proper index of the design challenges that exist within the building process, and a measure of the substantive breadth the design task must gain to respond to them. Secondly, because it would help form a view of the building project not tied a priori to specific actors but rather open to the recording of direct or indirect design contributions, to qualify in relation to the areas of impact. By creating the conditions for isolating and then bringing together the work conducted on disparate design domains by clusters of contributors, such a multi-dimensional view of design could be used as a tool to interrogate project challenges and results, eventually to intervene on the dynamics that led to them. The importance of the difference just articulated, essentially between 'design as product' and 'design as process', can be gauged effectively by returning to the sails of the building and the rhetoric surrounding their creation. While their canonical history celebrates the so-called 'spherical solution' as a stroke of genius on the side of the architect and the engineer, the story of the works put together by the contractor for their fabrication on-site tells a tale of work planning and ingenuity that counterbalances the myth of the 'eureka' moment by highlighting the amount of labour – intellectual as well as physical – required to make Utzon's great idea materialize.

Without taking anything away from the leap of imagination that led to the solution eventually employed, the actual construction of the sails owes a huge debt to the preparatory design and engineering work by the general contractor. Indeed, the spherical solution generated a series of significant construction chain challenges, from task identification to site planning, system engineering to visualization of decisions, work monitoring to quality control, which were all tackled by the main party 'on the ground'. Hornibrook did overcome the technical issues posed by the fabrication of all the parts required through the production of copious, detailed documentation based on and refined via a long period of prototyping work, which would be difficult to liquidate as mere, although remarkable, construction management.

8. Conclusions – From scrutiny to knowledge

If the analysis outlined can be seen as instrumental in reassessing the relevance of shop drawings as a design tool complementary (rather than subordinated) to architectural and structural drawings, the mechanics of their production and the multiple information exchanges required for their definition suggest the value of increasing our understanding of the construction process as design process, with its temporal dynamics as well as project-specific entities' interests and engagement in its resolution.

In contemporary practice, this type of reflective historiography is relatively within reach. Each phase of the design process, with its negotiations and autonomies, is today captured and stored in the form of drawings, specifications, and request for information on widespread used cloud-based platforms, such as Aconex or Project-Wise. Perhaps not the 'single source of truth' as self-promoted by their producers [43], these platforms surely perform as central archives where one can find the most organic representation of the contemporary design process, with all the technical and intellectual divisions of labour at work. As such, access to and analysis of the data they contain would be an effective way to build a documentary basis on the social complexity of design activity, from which a theory of contemporary design practice in a technologically participatory environment could ensue. As stated, the technology required to collect the data is available. But is there enough courage from the industry to open building projects up to this type of scrutiny?

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