Innovative construction and the role of boundary objects: A Gehry case study

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Abstract

Physical objects have long been used in addressing the challenges involved in constructing innovative buildings, yet their significance for collaborative problem solving in inter-organisational projects is rarely acknowledged. The aim of this research is to investigate what happens when a project team has to collaboratively innovate to address radical design challenges in a construction setting. We focus on the role of a full-scale mock-up of a façade in transforming the design intent for a building by Frank Gehry into design realisation. The concept of boundary objects is used as an analytical lens via a case study methodology utilising non-participant observation of weekly meetings and workshops over a period of ten months covering client, consultant, and contractor involvement. The research shows the role of mock-ups in radical construction settings is in tension along three delivery dimensions: performance, aesthetic and technical construction. Task completion competed with the requirements for experimentation around innovative problem solving with the *how to construct it* problem left unresolved. The findings suggest that co-location and synchronicity are critical conditions for collaborative and innovative problem solving in radical construction contexts. Project teams need to create open-ended 'moments' for iterating critical objects and the interactions that take place around them.

Keywords

boundary objects, construction innovation, inter-firm collaboration, Gehry

Introduction

Where complex and innovative building designs are involved there is an inherent need for collaborative and innovative problem solving amongst project participants. In turn, often there is no single driver or individual beneficiary of the innovations required as outcomes benefit the whole project team. The new Frank Gehry building for an Australian University [name omitted] offers a useful case in point. Its complexity is apparent in its radical shape: the floor plates have curvilinear edges resembling the shape of an amoeba while the same random curves also apply vertically over the full façade height of this 13 storey building (anonymous, 2015). These complex three-dimensional undulations are sheathed in traditional clay brickwork, a material not really suited to such distortion. In turn, large expanses of the brick skin are corbelled ranging from convex to concave shapes as well as undulating laterally and vertically to produce fissures and crevices intersected by glass curtain walls. This use of brickwork is unique both to this building and within Frank Gehry's existing oeuvre and, consequently, the project team had no prior experience to draw upon.

[Insert image 1 about here. Photo of the finished building]

Significant innovation was required to create a construction system to realise the architectural intent of the building façade (anonymous, 2015). For instance, the outer brick skin is affixed to a curved and twisted substructure made of steel stud framework with a sheet metal skin and an overlying waterproof membrane. The brick veneer is then supported at each slab edge via a steel ledger beam. It tracks up the curvature of the inner substructure, where newly developed and adjustable brick ties hold the brick skin a set distance off the substructure. These ties are held onto the stud wall using specially designed adjustable channels. Five new brick shapes had to be developed in order to build the tightly curved walls and to enable the ability to insert continuous reinforcing bars along each brick course.

Collaboration and innovative problem solving were clearly necessary to create the above system. Innovation in the construction industry, in general, is not implemented by one firm but involves a number of different firms working as a project team (Winch, 1998; Harty, 2008). In a study of inter-organisational projects which involved the production of high value, complex business-to-business capital goods, Hobday (2000, p. 873) explains that '"innovation actors" collaborate together taking innovation (e.g., new design) decisions in advance of and during production.' Consequently, in such settings, the focus for innovative work is on 'project-based problem solving' (Ling, 2003, p. 635) since it involves both design and production challenges for a project team. However, innovations in inter-organisational projects are inherently challenging and risky because each participating organisation has its own interests and expected rewards, making coordination extremely difficult (Dulaimi *et al*., 2003; Harty, 2008). One of the reasons given for the lack of innovation in the construction industry is said to 'stem from inadequate inter-organisational cooperation' (Barlow, 2000, p. 973).

A number of studies have documented the role of objects in supporting inter-organisational cooperation in innovative project settings (for example, Bijker, 1995; Carlile, 2002, 2004; Bechky, 2003a, b; Smulders and Bakker, 2012; Lenfle, 2014; Nicolini et al., 2014; Seidel and O'Mahoney, 2014; Scarbrough et al., 2015). These studies emphasise that material objects, such as models, mock-ups and prototypes enable the coordination of interdependent tasks, serve to visualise the innovative challenges teams face, and assist teams in developing new knowledge. The materialisation of ideas in innovative collaborative projects requires artefacts and interactions with them (Carlsen *et al*., 2012), which, in turn, facilitate experimentation (Lenfle, 2014; Seidel and O'Mahoney, 2014).

The focus of this research is on the role of a key object – in this case a full scale mock-up of the abovementioned brick façade – in transforming the architect's design idea into 'design realization' by a project team (Pietroforte *et al*., 2012). The aim of the study is to investigate what happens when a project team has to collaboratively innovate to address radical design challenges in a construction setting. Taking an extreme example, such as this, tests the application of the above findings in contexts, which have to date, been under-explored. The concept of boundary objects (Star and Griesemer, 1989) is used as an analytical lens to discuss the role played by the mock-up.

In the context of construction projects, mock-ups are known to assist with controlling and managing the construction process as well as provide a locus for learning and innovative problem solving (Keegan and Turner, 2002; Tryggestad *et al*., 2010; Pietroforte *et al*., 2012). Yet, how such objects fulfil these often conflicting roles and facilitate or inhibit innovative work is under-researched. As Bresnen and Harty (2010, p. 550) point out, while there has been an increased interest in the role of objects in construction projects (see CM&E Special Issue June 2010), studies that examine the 'constitution and role of objects in such distinct ways and/or [...] explore the conditions under which they might enable (or inhibit), mediate, constitute or actively promote joint activity' are still rare. Thus, the guiding question of this research is: what conditions enable a key object to support collaborative and innovative problem solving in the context of a radical architectural project?

To address the research question the paper begins with a brief theoretical outline of the nature of innovative problem solving in Frank Gehry's construction projects and the role objects play in such projects, followed by a discussion of how boundary objects are used more generally in innovative work. Next, the research design and method are described and the empirical data is presented to problematise the role of the mock-up as a boundary object in innovative problem solving. Following this, insights on conditions that work to diminish the role of boundary objects in radical innovative inter-organisational projects are developed and the implications these findings have for research and practice are outlined.

Innovative problem solving in construction projects: the case of a Gehry-designed building

The importance of innovation should not be underrated in terms of fostering the success of architecture and construction firms – it links directly to value-creation and long-term corporate interests (Loosemore, 2014). A study by Dulaimi et al. (2003) of the limitations and constraints on innovation in the Singapore construction industry explored the differences between innovation occurring within the single organisational practice and those that occurred in project settings – where more than one organisation was involved. They found that good inter-organisational interaction was a critical factor in the successful implementation of construction innovations. Authors such as Ling (2003) go as far as suggesting that innovation 'may become a fourth competitive dimension' (Ling, 2003, p. 635). For the clients of certain star architects a reputation for producing innovative architecture is already a key factor in influencing who they choose (McNeill, 2009). Innovative problem solving in the context of Gehry-designed projects puts different requirements on members of the project team including different ways of working together. Radical architecture, like radical innovation, requires the application of new knowledge and new ways of doing things – doing things differently in newly 'radical' ways constitutes the Gehry approach.

Coordinating inter-organisational cooperation for innovation is often challenging (see Seidel and O'Mahoney 2014 for an overview of research on product innovation), but it is in construction contexts, like this one, that issues of cooperation are attenuated when seen in tension with the 'intractable patterns' and 'inflexible sequences' of construction project management (Harty, 2008, p. 1033). Of note, construction is unlike innovation processes in manufacturing where design development takes place in dedicated jobbing workshops, testing facilities and computer-aided prototyping laboratories. Manufacturing principles that commonly separate production into discrete production modules are difficult to apply to the scale of something as radical as the aforementioned Gehry façade and its curvilinear brickwork. Furthermore, the design resolution required for large manufacturing runs is typically different to the 'one off' and bespoke nature required in radical construction projects (see also Hobday, 2000).

The construction process of innovative buildings, such as those designed by Frank Gehry, differ in a number of ways from standard construction practices. Conventionally, based on the architect's drawings, construction contractors create their own documents and shop drawings for the architect's approval to ensure that they are in compliance with the architect's design intent. In contrast, innovative architects like Frank Gehry draw upon advances in technology and construction techniques to design buildings that require continuous input from the project team and the development of new knowledge in order to be realised (Boland *et al.*, 2007; Berente *et al.*, 2010). Scholars of Gehry's design process recognise that his way of working requires innovative problem solving by construction teams to determine how his radical buildings can be built (Yoo *et al*., 2006; Boland *et al*., 2007). Accordingly, on Gehry projects the construction process is not the implementation of innovation (Ling, 2003) directed ‘from above’ by an ‘origin organization’ (Dulaimi *et al*., 2003) or a ‘system integrator’ (Harty, 2008), the Gehry firm, but rather a collaborative process of innovative problem solving by the project team necessary to progress Gehry’s design ideas into built form.

In sum, it can be said that Gehry’s radical architecture departs from standard practice in the following ways: it is conducted in an atypical ‘design and construct’ procurement system; it can be summarised as a ‘design-as-you-go’ approach; and, it occurs in an industry context practically oriented towards ‘known’ deliverables in tension with ‘uncertain’ innovative processes that require flexibility and malleability (Lenfle, 2014). In such circumstances tensions arise between the pragmatic delivery of construction (e.g. time, cost and quality) and the need to retain the integrity of the radical design intent.

While learning in innovative construction projects is still the result of jointly ‘trying things out’ (Rooke and Clark, 2005, p. 566), buildings and their parts are not necessarily plastic enough to be malleable, movable or amenable to rapid or on-going experimentation. For instance, project managers are usually eager to implement a design freeze as soon as possible, in order to allow the next stage of the project to take place. Since the Gehry project takes a different ‘design-as-you-go’ approach, the question of interest here is in how objects can mediate and support both innovative needs as well as the above-mentioned practicalities of project management.

The role of boundary objects in innovative project settings

To explain the role of objects in innovative construction settings the theoretical concept of boundary objects provides a useful explanatory framework. Of note, boundary objects have been recognised in supporting co-operation and coordination among multiple actors in both the literature on organisation and management studies (e.g., Carlile, 2002, 2004; Yakura, 2002; Bechky, 2003a, b; Swan *et al*., 2007), as well as in the literature on architecture, engineering and construction projects (e.g., Schmidt and Wagner, 2004; Barrett and Oborn, 2010; Bresnen, 2010; Luck, 2010; Whyte and Lobo, 2010; Walter and Styhre, 2013). The concept of boundary objects is particularly useful for the study of inter-organisational innovation because it explains how objects translate knowledge from one specialist knowledge domain to another (e.g., Swan *et al*., 2007) and assist team members in developing a shared understanding of the innovative problem (e.g., Carlile, 2002). An outstanding and relevant issue for this research is to what extent the framework can go further in supporting the more involved needs of collaboration for the purposes of innovative problem solving in construction.

Star and Griesemer (1989) first introduced the concept of boundary objects to explain how heterogeneity and co-operation coexist in scientific endeavours. In heterogeneous settings, including the current study, the concept of boundary objects is used to explain how diverse groups of actors from different backgrounds can co-operate. Two features of the concept are of particular interest here. First, Star and Griesemer (1989) stress the notion of interpretive flexibility: boundary objects are re-configurable and adaptable to local needs and individual interpretations, so each group of actors can use the objects to suit various needs (see also Pinch and Bijker, 1984). Second, it is held that boundary objects are useful for enabling co-operation without consensus (Star, 2010), allowing actors to tack back-and-forth between both group and individual perceptions of the object. Boundary objects, consequently, 'contain at every stage the traces of multiple viewpoints, translations and incomplete battles' (Star and Griesemer, 1989, p. 413). It is in their production and use that boundary objects enable teams to co-operate without reaching consensus.

Even so, further studies have stressed that apart from enabling cooperation without consensus, boundary objects in innovative projects need to facilitate additional collective practices to support teams in solving innovative problems. Carlile (2002; 2004) argues that boundary objects need to enable knowledge transformation in such contexts in order to be effective. More recently, Seidel and O'Mahoney (2014) stress that boundary objects need to be used with specific team practices to effectively coordinate innovation. For example, the collective scrutiny of objects empowers 'team members to understand novel concepts in new ways by inviting questions and reconciling disagreements' (p. 708), thus supporting the conversion of individual interpretations into joint action. Similarly, Lee and Amjadi (2014) posit that objects can motivate and stimulate real-time probing and experimental activities that expedite collective problem solving. These and further studies (Swan *et al*., 2007; Nicolini *et al*., 2012) demonstrate that the concept of boundary objects is particularly useful for the study of inter-organisational innovation because it explains how objects translate knowledge from one specialist knowledge domain to another as well as showing how they can be used to support experimentation.

Not all boundary objects, however, are seen as equally useful in innovative contexts. Some argue that only specific boundary objects, such as models, prototypes and maps, are able to support teams in breaking established assumptions and developing new knowledge, which are critical in innovative contexts (Carlile, 2002; 2004). Carlile argues this is because these types of objects enable ‘individuals to draw on, alter, or manipulate the content of a boundary object to apply what they know and transform the current knowledge used’ (Carlile, 2002, p. 452). According to Bechky (2003a, p. 327), such tangible objects are better suited for knowledge transformation and learning across diverse groups than written and verbal explanations because they provide a ‘concrete referent that individuals could manipulate to embed the understandings of others into their own understanding of their work context’ (see also Stigliani and Ravasi, 2012). This is clearly the position taken by this research because of the focus on a tangible object, a mock-up, as it applies to assisting collaboration in innovative problem solving.

Nevertheless, more recent studies have shown that the same type of boundary object can help achieve integration and learning *as well as* create misunderstandings and inhibit collective problem solving (e.g., Oswick and Robertson, 2009; Nicolini *et al.*, 2012; Fayard and Weeks, 2014; Seidel and O’Mahoney, 2014). These studies show that it is not only the type of boundary object that influences its effectiveness, but rather how it is *perceived* and subsequently *used* by different team members (Sapsed and Salter, 2004; Barrett and Oborn, 2010; Bresnen, 2010; Sage *et al.*, 2010; Styhre and Gluch, 2010; Nicolini *et al.*, 2012; Seidel and O’Mahoney, 2014). For example, Barrett and Oborn (2010) argue that when actors perceive a boundary object as rigid and fixed, this prevents them from engaging in the experimental collective practices needed in innovative projects. On the other hand, if an object is perceived as malleable and flexible, it can facilitate the above practices thus enabling collective collaboration and problem solving (e.g., Pinch and Bijker, 1984; Subrahmanian *et al*., 2003; Bresnen, 2010). How a specific boundary object is perceived depends on the 'circumstances and the parties' orientation to it' (Bresnen, 2010, p. 624; see also Orlikowski, 2000; Levina and Vaast 2005; Barrett and Oborn, 2010; Fayard and Weeks, 2014; Nicolini *et al*., 2014).

Researchers have demonstrated that to enable such collective practices, tangible objects and team members have to be co-located (e.g., Bechky, 2003a; Carlile, 2004; Lenfle, 2014). Co-location to boundary objects is important as it enables 'learning by doing' that can trigger the spontaneous relationships needed for inter-organisational collaboration (Levina and Vaast, 2005; Levina and Orlikowski, 2009). Bechky (2003a, p. 325) explains how team members' interactions with and around tangible objects enables the development of 'new understanding by raising questions about what the objects allowed or constrained and how they might be used or manipulated.' Through touching objects and physically demonstrating how they are constructed or work, team members from different backgrounds create common ground even when language fails: 'Tangible definitions allowed people to ground their divergent understandings in the physical world – essentially providing a concrete hook on which to hang their contextual interpretations' (Bechky, 2003a, p. 325; see also Lee and Amjadi, 2014).

While co-location of tangible objects with team members is indicated as an important condition in enabling team members to engage in collective practices, existing studies assume either that co-location already exists or that the boundary object can ‘travel’ (e.g. Yakura, 2002; Bechky, 2006; Vlaar et al., 2008). The condition of co-location has therefore not been problematised in existing research, and it is not clear whether a tangible object that is not co-located with a team can enable the above-discussed practices in innovative construction contexts. Accordingly, issues of flexibility or rigidity, distance or proximity, are of specific interest to this research because they focus on the potential assistance physical mock-ups provide in supporting construction innovation processes; and, because ‘the conditions under which [boundary objects] might enable (or inhibit), mediate, constitute or actively promote joint activity’ are not well-researched (Bresnen and Harty, 2010).

In sum, existing research shows that, to understand the effectiveness of boundary objects, it is necessary to study the specific conditions in which the boundary object is situated and used. In this study, the boundary object is not only a means for facilitating the innovative collaborative process; it also represents a necessary time and constructability test that must be passed in order to progress into actual construction on-site. Hence, the stage is set to study the mock-up as a boundary object for a team tasked with innovative problem solving in the context of radical architecture, in tension with controlling and managing time and resources in the delivery of a construction process.

Methodology

The empirical data employed for this paper is drawn from a larger longitudinal case study over four years on the design development and construction of the Gehry-designed building, as described in the introduction to the paper. The single case-study approach is supported by Flyvbjerg’s (2006) debate on the virtues of case-study research and the shortcomings of the hypothetico-deductive approach, in terms of its usefulness for generating and testing hypotheses and comparing theoretical findings with other case studies. These features are consistent with the stated aims of this research to investigate the conditions that enable boundary objects to support collaborative and innovative problem solving.

Qualitative researchers argue that study of a single case can not only provide insight into practice but also that it can have exemplary value where the case represents unusual access to a client–consultant relationship (Eisenhardt, 1989; Stokes and Perry, 2005; Yin, 2009). The present study represents such a case since close access to those involved in the project has been made possible by the research occurring within the authors' own academic institution, thus enabling situated, intense, and sustained observation of a process in action. Of note, the project represents an opportunity to explore the work methods employed by a 'star' architect, who is known for his complex and innovative façades.

Empirical data was gathered through non-participant observation of weekly meetings and workshops over a period of ten months including client, consultant, site, and contractor involvement. The period covers the construction, testing and interpretation of a performance mock-up of the building façade. This object is significant for study in three key ways: one, it is the first collective task of the project team and therefore also represents their learning to *be* a team being inculcated into Gehry's way of working; two, consequently, it provides a locus for team learning and collective innovative problem solving at a critical stage in a radical and complex architectural process; three, it represents the only formally planned process for resolving the complex façade whereby execution of it represents a distinct milestone in the project schedule. Despite their importance in innovative architecture and construction projects there are very few studies on the role of performance mock-ups in the construction literature (see Pietroforte *et al.*, 1992).

In addition to observation, recorded interviews with twelve members of the project team were undertaken including: two Gehry Partner architects, the Australian executive architect, two university executive-level clients, one university faculty head, two client project managers, two project managers from the construction company, one building contractor (responsible specifically for overseeing the construction of the performance mock-up) and the bricklaying contractor. As it was not possible for a researcher to be present at the Chinese testing site this information was gathered through: interviews; via non-participant observation of meetings of the project team preceding and subsequent to the mock-up's construction; the engineering consultants' reports including photos of the performance mock-up at several stages of its construction; and, the design architect's summary report. All interviews were audio recorded and transcribed. Due to the nature of the project and the commercial sensitivities involved, participants have been de-identified, although titles are used to differentiate roles performed.

The interview and document material was organised and managed using QSR software, *NVivo 10,* by the first two authors. Each author worked independently and all participated in regular meetings to discuss the coding. Analysis of the field material proceeded by reading and re-reading interview transcripts, field notes and meeting notes, to identify themes such as the nature of inter-organisational co-operation, the challenges of innovative construction projects and the role of the performance mock-up. The early coding offered general insights into project members' interpretations and use of the performance mock-up and their views on this stage of the building project and were used to clarify observations. An iterative process followed in which the authors moved back and forth between the field material, documents and analysis (Orton, 1997). After several rounds, three significant themes emerged: the construction of the performance mock-up as a milestone activity; the interpretations of the project team members on the role and effectiveness of the performance mock-up; and the lack of innovative problem solving around the object. These are discussed in turn.

Constructing the performance mock-up

In this project a performance mock-up was constructed as a 1:1 model and tested against a range of performance criteria, including air infiltration, static and dynamic water penetration, wind pressure, structural performance, seal degradation and seismic drift displacement. Although such mock-ups are becoming routine for certain practices, such as Gehry Partners, a mock-up at this scale and this level of investment was novel for most members of the Australian project team.

In the case under study, the four-month schedule for the construction of the performance mock-up was under pressure because of delays in other areas. Task completion was viewed as important to maintaining the project timeline so as not to impact either upon the building's completion date or the project budget. As one client project manager stressed, 'Every project is money in time. [...] that's the reality of the commercial nature of building'. However, certain members of the client team acknowledged that seeing the mock-up purely as a project milestone was problematic. As the senior project manager for the client explains:

> […] there's been a position that [] we should just get the performance mock-up built and sort out everything later, and I'm saying, 'No, the performance mock-up is to enable us to sort things out'.

As the façade contractor manufactures in China, and costs in the Australian building industry are high, it was decided that the performance mock-up would be built and tested in China. While this is not uncommon as many Australian façade companies outsource manufacturing to Asia, according to one client representative the designing architect was perplexed by the decision to build the performance mock-up off-shore and not closer to the building site: 'Frank said, "I don't understand […] they can make it in China [so] why can't they make it in Australia?"'

Individual members of the project team including two Gehry Partners architects, the consultant façade engineer, two representatives of the building contractor, the executive architect and the brick contractor travelled to China to observe the construction and testing of the performance mock-up – albeit not all at the same time. Of note, the lack of synchronised visits, coupled with their distance from the object itself, meant that team members were not co-located and able to physically interact with the performance mock-up all at the same time. Moreover, due to the geographical dislocation between object and team, team members spent limited time at the site. The brick contractor was the only team member who spent more time at the testing facility (more than a month), having to source, train and manage a local team of Chinese bricklayers to construct the brick skin of the mock-up (necessary due to labour laws in China that precluded flying in his Australian team). The senior project manager for the client, while originally intending to travel to China, eventually decided against going – for cost reasons.

As the object and the team were not co-located, and team members visited at different times, problems that arose generally did so in the intervals between such visits. For example, when the engineer arrived after construction was well underway he identified non-compliance issues and halted work for a few weeks. This lead to tensions in the project team; many felt they should simply forge ahead, 'get the performance mock-up built now and sort out all the problems later.' In this way, task completion within the prescribed project schedule became the dominant focus.

Team members' interpretations of the performance mock-up

As team members' collective and individual interactions with the object were limited, team members used the performance mock-up to address issues that were critical for their specific role in the project. For example, Gehry Partners used the performance mock-up as another design verification tool, i.e. to confirm the aesthetics of the building as this was one of their main concerns: 'One is aesthetics; it gives everybody at the same point and time to understand how all these different elements are coming together and what it ultimately looks like' (Gehry Partners design architect).

The executive architect, whose role was to 'translate' between the Australia-based construction team and the US-based design architects, used the performance mock-up as a test of the ability of the team to collaborate: '[It] has highlighted …that Gehry Partner's documentation is just that, design documentation … [you] can't build off it'. As the mock-up demonstrated that the Australia-based members of the team did not properly understand the Gehry Partners' design approach, the executive architect became focused on how to help eliminate such misunderstandings.

For the building contractor representative, who joined the rest of the team after the construction of the performance mock-up had commenced, the mock-up provided a valuable opportunity to get to know the rest of the team and in particular, the design architects:

> I was keen to go [to China] at least once in the [performance mock-up] stage, primarily from a relationship point of view, to meet up with the Gehry representatives. [] A performance mock-up is a normal industry practice. [] there's the technical side, but there's also the relationships side []. So from that point of view, it was a relationship issue []. Understanding where Gehry are coming from, not just on design issues, but just how they communicate or the frame of reference they have is good too.

Several team members used the performance mock-up as a risk management tool. For these members of the team the risk of undertaking such an innovative building project was significant, and they saw the performance mock-up as a way to minimise the organisational risk associated with their role in the project. For example, the engineering consultants responsible for the façade focused on shortcomings in how the performance mock-up was constructed and requested a number of changes. Other team members did not perceive these shortcomings as critical issues at this stage of the project. They argued that the engineers were mainly trying to minimise their risk. The bricklayer, who was not yet officially contracted, used the performance mock-up to better understand the work required and as an aid for pricing the work, thus minimising their risk. For the executive client, who had an overall responsibility for the successful delivery of the building to the client, the performance mock-up served as a demonstration that the building could be constructed successfully: ‘We need the [performance mock-up] [] to enable us to give the comfort. We don’t know how we’re going to build [the building] otherwise. [] You can’t build these buildings without the models.’

By integrating the work of specialised team members while enabling them to focus on specific issues related to their role in the project, the performance mock-up fulfilled the role of a boundary object. It enabled the main elements of the building to be visualised and was used by individual team members to address specific issues related to their task responsibilities. In terms of time efficiency, this enabled the project manager to ‘tick off’ stages of progress. However, whilst these features variously fulfilled self-interest and timeline expediency, the mock-up did not facilitate collaborative interaction in terms of generating answers to the question of *how* to build the innovative façade. It fell short in terms of helping actors to negotiate individual and collective responsibilities and to transform their existing knowledge.

The boundary object and the lack of innovative problem solving

As mentioned above, the performance mock-up was the first opportunity for the project team to work co-operatively in terms of testing their ability to construct the innovative building design. For instance, to date it had only been represented in models created by the designers. As such, the performance mock-up was supposed to help the team physically realise the innovative aspects of the building façade, as explained by one of the client’s project managers:

> The PMU [performance mock-up] itself, is a valuable tool, in terms of understanding how things go together. So there's a commercial requirement, or a contractual requirement to test the PMU itself, but beyond that there's also knowledge to be gained out of how the bits and pieces go together. So there's a whole process in terms of what you see on paper being translated into the actual physical elements, and that process of translation from the paper document to the finished product, and the steps in there is where you gain all of this. You take knowledge that you already have, which is the standard brick laying, curtain wall installation knowledge, and you apply it to that particular exercise, and then you start to learn what works and what doesn't, and what you need to improvise on or change or adjust, or develop as you go. So that's something that you can only do through that process. [] You can't learn it from paper.

However, a key question that should have been addressed by the performance mock-up, that is, how to construct the innovative brick skin of the building, was not resolved. The performance mock-up had been constructed as a 'typical' and relatively straightforward section of the façade and not one of the more extreme undulating sections. As one of the building company managers explained, more could have been learnt if the mock-up had represented the most complex or demanding sections: 'I sort of feel that we would have got more value out of it, if we'd tested some of the more extreme shapes of the brick.'

Other team members commented on the shortcomings of the performance mock-up as well. One of the client project managers stated, 'It's not a true representation of what we are going to build.' [] 'the base structure for it wasn't built exactly as the base structure that we are going to apply the building to.' The executive architect explained, that ‘The [performance mock-up] is being used as another visual mock-up to tie in elements. There were portions that were misinterpreted; there was misunderstanding about the intent of the visual mock-up and the process.’

[Insert figures 2, 3 & 4 about here. The performance mock-up under construction, completed and with testing rig in place]

Despite these shortcomings, the performance mock-up helped the project team gain important insights for the next stages of the project. First, team members gained insights into those aspects of the mock-up that did not perform as required. Second, the team realised the implications of the Gehry Partner’s ‘design-as-you-go’ approach: that, in contrast to standard construction practice, the architects’ drawings did not answer *how* to construct the building. Through the team’s experience of working on the performance mock-up it became clear that figuring out how to construct the façade required an intensive collaborative effort and an integration of the knowledge and experience of the whole team. Third, and critically, it became clear the team still didn’t have the answer how to solve a range of technical challenges that the façade presented including brick shapes, waterproofing and the structural role of brick ties in preventing the brickwork from rolling outwards.

Discussion

The findings from the empirical work are premised by the overriding context of the situation, namely a radical building design and the application of a ‘design-as-you-go’ approach to delivery of the design.

Team participants were relatively new to this approach as they were normally used to having a more fully resolved design passed along the supply chain in a relatively linear fashion. However, in this case, they were targeted as co-innovators in the design to realisation process where normative practice was of limited relevance. The mock-up was the only formally planned attempt at resolving the needs of the radically shaped façade but, to an extent, it ultimately meant different things to different participants. Of importance, three key roles expected of the mock-up stood out: 1) Proof of functional performance (compliance and technical performance); 2) Ensuring that the aesthetic integrity of the design was preserved; and, 3) A vehicle for understanding and developing methods of how to physically construct the design (including non-standard technical, process and componentry questions). The least attended of the abovementioned areas was the need to understand how to construct the design, albeit that it was the area that required the most attention in terms of innovative problem solving.

In reviewing the boundary object literature and the realities that occurred within the above context, it can be said that the mock-up indeed acted as a boundary object in a number of ways. Cooperation and coordination of interdependent tasks (Star and Griesemer, 1989; Star, 2010) were clearly apparent but mainly for the functional performance aspect of the mock-up. At a broader level, the mock-up served to visualise the innovative challenges faced by the team in both learning and developing new knowledge (Carlile, 2002, 2004; Bechky, 2003a, b; Ewenstein and Whyte, 2009; Pietroforte *et al.*, 2012), and this was the case across all three areas mentioned above. For instance, even in the under-attended area concerning how to construct the façade, the team realised what had not been achieved by the mock-up and now had a stronger understanding of what needed to be done (i.e. understanding about the complex shapes, associated technical questions and modified site processes).

Even so, the mock-up was ultimately perceived as being rigid more so than flexible which restricted the way the team used it (see also Barrett and Oborn, 2010; Bresnen, 2010). The role of the object was seen as static – to enable testing against specified criteria and to ensure that the aesthetic integrity of the design was preserved. Thus the role of the mock-up never evolved to support the collective practices required for innovative problem solving (see also Scarbrough *et al*., 2015). Time constraints surrounding delivery of the mock-up and the fact that it was a contractually binding milestone seemed to exacerbate this perception (see also Barrett and Oborn, 2010). Whilst it adequately met the needs of resolving functional performance issues, the mock-up was not used for experimentation in understanding the *how to construct it* problem. It limited the ability to facilitate collaborative and innovative problem solving and left unanswered questions: the lack of a fully resolved method of construction meant that fine-grained architectural detailing – vitally important in achieving high level aesthetics – remained indeterminate.

Finally, the core situation in which team members were not concurrently co-located, or localised relative to the mock-up, had a blanketing effect that also limited the capacity for collaborative and innovative problem solving (including the above perception of rigidity rather than flexibility). Only the bricklaying contractor, who was directly involved in building the mock-up and spent more than a month on site, was able to walk away with an experiential understanding of the issues involved and the challenges posed by the radical design. What happened could be best described as a centrally located object visited by the team in a lineal rather than concurrent way. In a sense, this approach is consistent with normative industry practice and contractual supply chain boundaries alluded to previously that tend to force linearity in the supply chain. Hence, individual problem solving tended to be role-specific rather than the collaborative and innovative problem solving required of the *how to construct it* problem. In practical terms this meant team members did not tack between their versions of the object – it was too far away and therefore 'unclaimed' in terms of providing an engaging place for concurrent collaboration.

These findings show that the construction of the performance mock-up was a lost opportunity to resolve a critical and pressing issue the team faced concerning how to construct the façade. The abovementioned lack of resolution did not make the problem go away; it simply saw the problem shift back to Australian shores.

Conclusion

This research explored two central themes. That is, the nature of inter-organisational co-operation in a radically designed architectural project, and the role of boundary objects (in this case a full scale mock-up of a complicated curvilinear brick façade) in assisting collaborative and innovative problem solving. These themes are set within the context of a design-as-you-go approach to construction procurement that sees the construction supply chain act as co-innovators, as distinct from more normal supply chain arrangements. The study found that while participants sought different outcomes from the mock-up itself, the key concerns were proof of functional performance, ensuring that the aesthetic integrity of the design was preserved, and understanding how to physically construct the radical facade. The last of these required most attention in terms of innovative problem solving but was ultimately the least attended aspect of the boundary object.

This study underpins known features of boundary objects including cooperation, coordination and visualisation which all work towards translating a degree of new knowledge (Carlile, 2002; 2004; Swan *et al*., 2007). Even so, in this case, the boundary object fell short in enabling higher-level collaboration around innovative problem solving (mainly concerning the *how to construct it* question). Here it seems that where collaboration surrounding innovative problem solving is involved there is first, the issue of how objects are perceived and used (see also Sapsed and Salter, 2004; Barrett and Oborn, 2010; Bresnen, 2010) and second, the issue of the conditions in which boundary objects are created. As these two issues exist in tension, the conditions that influence how boundary objects are perceived and used in innovative settings thus deserves further attention.

Sustained analysis of the processes around the creation of the mock-up and the above issues illustrated the significance of two contextual conditions relating to the project: the team's co-location with a significant boundary object (see also Bechky, 2003a; Lenfle, 2014), and the allocation of time and resources for team members to engage with that key object (Bakker *et al*., 2013; Scarbrough *et al*., 2015). These findings have not been empirically demonstrated before in a radical design and construction setting. This study shows that when teams and objects are not concurrently located, and team members focus on task completion rather than on experimentation, innovative problem solving does not occur.

This suggests that inter-organisational innovation requires *more* than objects and *more* than teams in ways that recognise the specificities and contextual constraints of construction settings. It is well known that timeliness is a key performance requirement on construction projects. A key message, therefore, is that the pressure to finish the performance mock-up quickly and to construct it more efficiently (i.e., overseas) was in direct tension with the ability of the team to act synchronistically and collaboratively with it.

In innovative building projects ways need to be found to speed up innovative processes. In inter-organisational projects, in which global firms are increasingly viewed not only as necessary but also as desirable, with team members and key objects likewise dispersed, new practices or new ways of organising existing practices are needed. A key issue is therefore how to manage the definition, staging and integration of key objects in the time planning of innovative projects. Ways need to be found to quarantine time for iteration, prototyping and experimentation as part of, but not in conflict with, the building schedule. In this way boundary objects would be empowered to structure not only work outcomes but also work processes.

In these ways certain anomalies in the organisation, management and construction literatures on how project teams work become apparent. In theory, design activities and pre-construction activities (such as construction sequencing and time scheduling) are based mostly on explicit knowledge that is assumed to be predictive (Hartman and Fisher, 2007). In other words, design intents and construction plans must be deemed to be constructible and feasible. In practice, such predictions do not fully eliminate the uncertainty driven by the uniquely contingent design requirements of a radically designed building, as dealt with in this research. Striving to completely eliminate uncertainty on radically designed projects, such as this, is misconceived. Instead, it is important to acknowledge that design and construction, on such projects, are united in a recursive process and construction management needs to be handled accordingly.

The study makes three contributions to the existing literature. First, it identifies the role of mock-ups where radical architecture must be resolved as part of on-going construction processes (including performance, aesthetic and technical construction delivery dimensions). Despite mock-ups being critically important in innovative design, architecture and construction settings, there is very limited research on the exact role these objects play. Given the significant investments in the construction of full-scale mock-ups, it is important that their role and purpose are well understood so they can be used effectively.

Second, the study elucidates the conditions that work to qualify the ability of boundary objects to enable successful collaboration in innovative construction settings. In this way, the research builds upon and extends existing research on the effectiveness of boundary objects in innovative construction projects (Harty, 2005, 2008; Tryggestad *et al*., 2010), as well as innovative projects more generally (e.g., Carlile, 2002; Swan *et al*., 2007; Seidel and O'Mahoney, 2014; Scarbrough *et al*., 2015).

Third, the study shows that standard project management practices of task completion exist in tension with the requirements for experimentation and innovative problem solving (see also Lenfle, 2014; Scarbrough *et al*., 2015). Thus, attention to objects needs to be tailored according to one or more needs, as does interaction around them. In this way, the study addresses a gap in the literature regarding how innovative problem solving in design and construct settings occurs (Harty, 2008).

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Figure 1. Photo of the finished building

Figure 1. Performance mock-up under construction in China.

Figure 2. Finished mock-up prior to testing.

Figure 3. Testing rigs to direct water and air onto the façade being put into position.