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Visualizing practices in project-based design: tracing connections through cascades of visual representations

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ABSTRACT
Project-based design involves a variety of visual representations, which are evolved to make decisions and accomplish project objectives. Yet, such mediated and distributed ways of working are difficult to capture through ethnographies that examine situated design. A novel approach is developed that follows cascades of visual representations, and this is illustrated through two empirical studies. In the first case, Heathrow Terminal 5, analysis starts from paper- and model-work used to develop design, tracing connections forward to an assembly manual that forms a 'consolidated cascade' of visual representations. In the second, the Turning Torso, Malmö, analysis starts from a planning document, tracing connections backward to the paper- and model-work done to produce this consolidated cascade. This work makes a twofold contribution: first, it offers a methodological approach that supplements ethnographies of situated design. This allows the researcher to be nimble, tracing connections across complex engineering projects; reconstructing practices through their visual representations; and observing their effects. Second, it articulates how, in these empirical cases, interaction with a cascade of visual representations enabled participants in project-based design to develop and share understanding. The complexity of projects and their distributed and mediated nature makes this approach timely and important in addressing new research questions and practical challenges.

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Introduction

Visual representations are crucial to processes of designing and organizing. By making information visible in front of others' eyes, the most compelling images can muster 'the largest number of well aligned and faithful allies' (Latour, 1986, p. 4). Recent research has articulated the role of visual representations in organizing (Meyer *et al.*, 2013; Ravasi and Stigliani, 2012; Styhre, 2010) and a rich trajectory of research on drawings and other forms of visual representations has emerged in project-based design (Enberg *et al.*, 2006; Jönsson, 2004; Tryggestad *et al.*, 2010; Justesen and Mouritsen, 2009; Whyte *et al.*, 2007; Dossick and Neff, 2011; Yakura, 2002; Luck, 2007; Harty and Tryggestad, 2015). Much of this research uses ethnographic methods to examine the situated practices of designing and organizing in a particular place and time. This work has extended our understanding, for example in relation to the patterns of interaction between designers and users (Luck, 2007); the role of visual representations in the power dynamics of design practice (Sage and Dainty, 2012); the translation between different forms of representation (Justesen and Mouritsen, 2009); and the epistemic and boundary-spanning roles of visual representations (Ewenstein and Whyte, 2009). Yet the mediated and distributed ways of working through which project-based design is now accomplished are difficult to capture through ethnographies that examine such situated practices.

Engineering projects are complex. The teams involved in projects are often not co-located, but may be distributed across extended supply chains that involve many organizations spread out across different geographies. In this context, visualizations are evolved through practice, multiply, become increasingly collated and enriched in more reified and hybrid forms, become linked together, and circulate across localities and stakeholders, including the supply chain involved in fabrication, assembly, and on-site work, and the external sponsors such as clients, insurance companies, and public authorities. New visual practices are emerging with digital representations being developed in a range of software, including building information modelling (BIM) (Dossick and Neff, 2011) and PowerPoint (Kaplan, 2010; Gabriel, 2008), and being evolved through diverse

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hardware, ranging from projectors and computer screens to mobile devices such as tablets and smartphones. Thus, in project-based design practice, visual representations are increasingly distributed across a variety of digital and physical media and are evolved to make decisions and accomplish project work.

How can we understand the cascade of representations through which project-based design work is accomplished? The contribution of this paper is twofold: Firstly, it offers a methodological approach for following the cascading of visual representations. This allows the researcher to be nimble, tracing connections across complex engineering projects; reconstructing practices through their visual representations; and observing their effects. Secondly, it articulates how, in two empirical cases of design and engineering projects, interaction with a cascade of visual representations enabled participants to develop and share understanding. This involves highlighting the roles of paper- and model-work in forming a 'consolidated cascade' of visual representations involved in accomplishing project-based design.

The structure of our paper is as follows. In the next section, we review the theoretical issues underlying visual representations and visual practices, and approaches to understanding their roles in project-based design. Afterwards, we introduce our research contexts, the roof subproject at Heathrow Terminal 5 (T5), London, UK, and the Turning Torso project, Malmö, Sweden; and give an overview of our approach to tracing connections. We then use examples from our findings to observe the effects of visual representations and trace connections across a cascade of visual representations. The concluding section summarizes and discusses the contributions of the paper by highlighting the pivotal role of 'model-work' and 'paper-work' in a cascade of visual representations and by discussing the timeliness and importance of tracing connections through time and space, rather than by observing situated practices at a given time and space.

Theoretical background and current approaches

Within the rich trajectory of research on drawings and other forms of visual representation, many studies take an ethnographic approach, observing the actors within an organizational setting and seeking to give voice to their experience. For example, Yaneva (2009) describes her commitment to undertake a process of 'slow observation and analysis' (p. 14) within an architectural practice, observing the effects of model-work. Likewise, Groleau *et al.* (2012) observe architects using visual representations over a six-month period, two days a week, with particular attention to how an intern used 3D software. Others focus on visual representations in meetings: Garreau *et al.* (2015) accessed these through a business office acting as development client, and Ewenstein and Whyte (2009) through an architectural firm. There is a growing use of video ethnography as a way of capturing even richer and more detailed data on social interaction in design and organizational practices (LeBaron and Whittington, 2009; Smets *et al.*, 2014).

Such detailed focus has enabled substantial insight on what is done with visual representations in particular places and times. Yet digitally mediated and distributed ways of working are difficult to capture through situated ethnographies. Increasing focus on visual practices within specific organizational settings provides limited understanding of how they become elaborated and circulate across localities and stakeholders. Our approach, on the other hand, draws on work about multi-sited ethnography, which suggests following the interactions of interest across ecologies of practices (Marcus, 1995). This extends the empirical focus beyond the 'here and now' of situated interactions, and challenges the assumption of privileged insight that comes from the anthropological roots of the ethnographic approach.

But instead of following human actors as in current multi-sited ethnographies (Marcus, 1995), we follow visual representations – which carry the evidence of work that was previously accomplished (Christensen, 2012). The visual representations from the field provide evidence of unfolding design practices across organizational settings. They 'support or prevent collaboration of different and, at times, distant parties and interests' (Nicolini, 2007, p. 576). In particular, we aim to articulate an approach to tracing connections by following the cascading of visual representations, and their progressive consolidation (or stabilisation). This involves understanding the roles that paper- and model-work play in creating a 'consolidated cascade' of visual representations throughout project design. To prepare the ground for our contribution, in what follows we take a closer look at the theoretical and methodological issues underlying visual representations and visual practices.

Visual representations, paper-work and model-work

Current research on visual representations and visual practices integrate insights from multiple disciplines, ranging from art theory, to design studies, sociology, and organization studies. Art theorists focus primarily on dissecting and analysing elements of the image, and use such elements to infer the nature of the practices in which the image itself is mobilized (Tufte, 1997; Elkins, 1999). Elkins (1999) argues that all images consist of a combination of pictures, notations, and texts, where *pictures* involve forms, colours, shades, and tones; *notations* involve diagrams, maps, and systems of shared symbols, such as musical notation; and *writing* involves the representation of fully developed alphabetic or character-based spoken language. These three aspects are seen as never isolated and pure but always experienced in hybrid forms (Elkins, 1999, p. 236). For example, every text has pictorial elements: meaning is conveyed not only in the *words*, but also in their *form*, the layout of the text on the page, and the typefaces used. Following Elkins (1999), images are not texts to be decoded, but rather texts are part of the wider category of images.

Attention to the visual within organization studies (e.g. Meyer *et al.*, 2013; Styhre, 2010) stems, in part, from a resurgence of scholarly interest in practice, which has recognized both its socio-material nature (Orlikowski, 2007; Orlikowski, 2010) and that aesthetic forms of knowledge and knowing play significant roles (e.g. Ewenstein and Whyte, 2007; Hancock, 2005; Gagliardi, 1996; Strati, 1999). Such literature on visual practices draws on studies of professional work that articulate people's use of and interactions with visual representations (Bødker, 1998; Henderson, 1999; Eckert and Boujut, 2003) and the gaze of different participants (Goodwin, 2000).

Terms such as representation, model, drawing, simulation, and artefact have different definitions and connotations across the literatures. For scholars of design practice, the image is always a *representation* of 'something else', that is manipulated and changed on its behalf (Oxman, 2002; Tovey *et al.*, 2003). *Models*, *drawings*, and *simulations* are sub-sets of representations. Design models are three dimensions and drawings are two dimensions. They may be experienced statically, or may possess a temporal quality (i.e. involve simulation). *Artefacts* are objects that are made by people. An artefact, such as a piece of paper or a computer screen, may have on itself many representations. These representations represent or signify something else, which may be existing or proposed. They abstract and transform the other that they represent, revealing underlying rules and concepts. In architectural design, the 'other' may be a building, which is often modelled in three dimensions, though views of such models may also be represented in two dimensions. Design is understood to be achieved in practice through a range of models, drawings, and simulations (Whyte, 2015).

Scheer (2014), in contrast, draws on sociological theories to argue that representations abstract and allow for exploration at depth, whereas simulations stand in for the things being represented. The sociological literatures emphasize the superficiality of simulation (Baudrillard 1983), and note an immense accumulation of spectacles (Debord, 1994 [1976]) at the societal level. Scheer (2014) suggests that drawings are representations while computational designs are simulations, but such distinctions blur in the practice of building design (Whyte, 2015). We believe that it is an empirical rather than a theoretical matter whether any representation becomes used for exploration at depth or a substitute for what it represents.

In this paper, we follow the approach of practice scholars (mainly across design and organization studies) in focusing on the work – the tasks that people are doing through using visual representations and the multiple settings within which this work takes place (Nicolini, 2012). From a practice-based perspective, knowledge is not so much something that can be codified, but something that can be *re-presented*, in ways that are to varying degrees ambiguous, contingent, and partial. This is important, where the visual has been used as a powerful metaphor in theories of knowledge: we talk of insight and illumination, speculation, reflection, focus, and point of view. Yet it is difficult to untangle the locus of knowledge in any practice. Visual representations are experienced in multi-sensory social settings. They form a part of embodied practices in organizations (Yakhlef, 2010) and play a critical role in mobilizing interest and creating understanding among stakeholders.

The practice perspective draws on suggestions from actor-network theory (Latour, 2005), which indicates that images fix a communicative intent, thereby enabling meaning to be distributed across space and time to others. In explaining the process of persuasion, Latour (1986) draws attention to how such representations may be 'immutable when they move, or at least everything is done to obtain this result' (p. 21) in order that 'all the instants of time and all the places in space can be gathered in another time and place' (p. 19). Meaning is not the same as its representation, but representation involves an attempt to stabilize the meaning by freezing the image. Researchers emphasize and conceptualize the frozen quality of the images: Latour (1986) describes them as 'immutable mobiles' created through the craft of writing and imaging and Levy (1994) draws attention to the important role of fixity in both digital and physical documents.

Fixity is the result of an output of increasingly simplified and increasingly costly representations. As reifications of meaning (Wenger, 1998), visual representations become a focus for negotiation and hence can be an important resource for change. As this happens, work is done to alter or annotate them, or to produce further images to better convey the evolving meaning. This work can occur to a single representation and also –

more commonly – to a linked, directional chain (Goodwin, 2000), or *cascade* (Latour, 1986) of representations. Visual representations are thus among the host of objects that are involved in this negotiation of meaning (Amman and Knorr-Cetina, 1988; Knorr Cetina, 1999; Rheinberger, 1997). They play a trans-epistemic role, allowing different inputs from across communities and unfolding through their use (Ewenstein and Whyte, 2009); their ambiguities becoming a resource for change and development.

The 'paper-work' and 'model-work' performed in design projects are central to producing a cascade of visual representations, and enable consolidating such a cascade into increasingly stable or fixed images. Latour (1986) notes that two-dimensional (2D) representations on paper are instrumental for mobilizing allies, because they are: (1) mobile, (2) immutable, (3) made flat, (4) scalable, (5) reproducible and distributable at little cost, and because they are possible to (6) reshuffle and recombine, (7) superimpose regardless of origins and scales, (8) make part of a written text, and (9) merge with geometry. In particular, Latour (1986, p. 21) argues that:

> "Thinking is hand-work", as Heidegger said, but what is in the hands are inscriptions. Levi-Strauss's theories of savages are an artifact of card indexing at the College de France, exactly as Ramist's method is, for Ong, an artifact of the prints accumulated at the Sorbonne; or modern taxonomy a result of the bookkeeping undertaken amongst other places at Kew Gardens.

For Latour (1986, p. 21), 'Most of what we impute to connections in the mind may be explained by this reshuffling of inscriptions that share an "optical consistency".'

While Latour's (1986) work on the consolidated cascade emphasizes the value of 2D representations and 'paper-work', recent studies of visual representations in construction highlight the increasingly important role of 3D representations and 'model-work' (Tryggestad *et al.*, 2010; Justesen and Mouritsen, 2009; Whyte *et al.*, 2007; Dossick and Neff, 2011; Harty and Tryggestad, 2015). For example, Yaneva (2005) noted how the scaling up and scaling down of physical models enable architects and other designers to work out decisions across multiple models and at different scales. Recent studies showed how the introduction of software for 3D modelling in architectural design created tension between institutionalized and emergent practices of organizing (Grouleau *et al.*, 2012), and led architects to devise hybrid practices of designing (Harty and Whyte, 2010) that involve shifting across digital and physical models (e.g. computer models and cardboard models). As several scholars in organizational studies (e.g. Barley, 1990; Lanzara, 2009) and art theory (e.g. Hockney, 2001) have pointed out, the changing technologies through which representations are modelled, manipulated, distributed, and interpreted have wide-reaching consequences for practices of designing and organizing.

Methodological issues

Methods of analysis have always relied on ways of visualizing data. Kavanagh (2004) describes the emphasis on writing as part of a wider ocular-centrism in Western thought, as writing is largely a visual exercise, unlike speaking, which is centred on hearing. The translation of interview data, from audio files into transcripts, is part of a process of making data visual. There is an increasing interest in articulating the methods used in the collection and analysis of visual data (e.g. Banks, 2007), with new methods being developed for capturing, storing, and analysing extensive visual data, for example through photographs taken by participants (Warren, 2008) or through video (Jönsson, 2004). Yet these approaches can have an impact on the practices of participants, as discussed in relation to a video study of a hospital setting by Iedema and Rhodes (2010). They also focus attention on interactions over short periods, rather than the shifts that occur over longer durations. It is this increasing instrumentation and intensity of focus on one place and time that we seek to resist in order to develop new knowledge about the cascade of representations through which design work is accomplished in complex projects.

Our 'tracking' strategy is to follow interactions around the visual representations, rather than to 'follow the people'. Rather than focusing on a particular place and time, we aim to tracing connections between these localities (Latour, 2005). These connections are hard-won, involving reflective practices in research throughout the data collection and analysis stages, as choices are constantly being made about the focus of attention, and the nature of the analysis. Rather than following individuals that are embedded with a particular local practice, this approach allows the researcher to make choices and move quickly to follow relevant interactions in the field by travelling across local practices. This is crucial to explore how project-based work is evolved through visual representations that are distributed in space and scattered across media.

In order to trace connections through a cascade of visual representations, we rely on previously established concepts such as 'paper-work', 'model-work', and 'consolidated cascade' (see the previous section). We proceed both forward and backward, from the paper- and model-work into a consolidated cascade of visual representations, and from a consolidated cascade of visual representations back into the paper- and model-work entailed to making such a cascade. Tracing the cascade of visual representations (whether forwards or backwards) is not a traditional ethnographic approach, as it rejects the strong assumption that the place in which you are is the place in which the action occurs (Czarniawska, 2007). Instead, our approach is both an alternative and a complement to ethnographies of situated design, as it involves travelling across space and time rather than engaging exclusively in the 'here and now' of one specific situated interaction.

Our approach builds on an ecological approach that is informed by practice theory and related streams of research such as actor-network theory, and is focused on the observation of the phenomena of interest. It involves maintaining a focus on the unfolding of connections across places and localities, a commitment to a contextual understanding of participants, as well as a deep engagement with the field – as an evolving set of dynamic links to guard against coming to conclusions too early, too quickly, without taking into account interconnected aspects (and the dynamic unfolding of such interconnections). This is enacted in the field by using visual representations as the foundation for productive interview conversation, for example by bringing the camera to the field or by asking participants to comment on their own visual representations, to assist the researcher in making connections backwards and to prepare their understanding of forward moves.

The methodological challenges and implications of this approach concern how to capture the role of visual representations, and with what equipment. Thus, in our own work, we have sought to 'travel nimbly', by using a digital camera, a notepad, and materials from the field, or by tracing multiple versions of architectural drawings in order to capture the progressive elaboration of the design projects. When confronted with visual representations from our datasets, it is relevant to reflect on the ways in which these visual devices entered and were used reflectively in our own research analysis practices. It is also important to consider whether researchers use their own devices (e.g. camera) to produce and negotiate new images based on the images from the field, as part of the process of ongoing sensemaking, and whether they are able to reproduce the 'found' visual representations.

In the next section, we illustrate our approach through examples from two studies that we have recently completed (Heathrow Terminal 5 project, London, and the Turning Torso project, Malmö). Both these studies generated a set of data that included visual representations produced by researchers through field work (e.g. photographs, field notes, sketches on whiteboards) as well as images that were produced by participants on the field, in the form of plans, models, graphics, photographs, and hybrid representations (e.g. digital and physical). We will examine examples from these studies to clarify how actions, talk, and consolidated cascades of visual representations (as well as the paper- and model-work involved in their construction) are dynamically connected in project-based design. By drawing on these case studies, we seek to explicate relationships between representations and actions (e.g. design decision), as these representations are themselves evolved and changed.

Research context: management and design work

The paper draws on two studies that were conducted in complex engineering project organizations. The contexts of these studies are:

- The Heathrow T5 project, which opened as a new terminal at London Heathrow airport in 2008, involved an initiative to introduce a central data repository to ensure that design decisions were documented, the latest versions of drawings were available, and interactions between sub-projects were managed. The roof sub-project was described as a particularly good example of the use of this 'single model environment'.
- The Turning Torso project, which became part of the Malmö city plan at the turn of the millennium, was the highest apartment tower in Europe. In the local context of Malmö city, the 196-m high building construction represented a significant change in both the city's skyline and building norms. Until then, the building norm was defined by the highest building that measured 77 m.

The first study was conducted from a practice-based perspective, with a particular interest in visual practice, with aspects of actor-network theory influencing data analysis and interpretation (Whyte, 2013; Whyte and Harty, 2012; Harty and Whyte, 2010). In this study, the logic of analysis involved 'model-work' as a starting point, traced through development to the consolidated cascade. The empirical work was conducted, initially with a focus on T5 as part of a larger research team, with other outputs (e.g. Davies *et al.*, 2009), and then with a specific focus on the single model environment and roof sub-project (Whyte, 2013). In this study, the first phase of data collection involved 30 interviews with senior managers and the second phase involved document studies, *in situ* visits, and more than 20 interviews. Data collection took a year and a half and the documentary data included presentations of the project to external stakeholders, photographs, and videos from the architect, more than 500 pages of internal documents from the client and contractor, and press releases, and articles from magazines and the local newspapers.

In the second study, actor-network theory influenced all stages of project set-up, data collection, and analysis (Tryggestad *et al.*, 2010; Tryggestad and Georg, 2011; Georg and Tryggestad, 2009). A planning document depicting a map of Malmö city's Western harbour and a projection of its future is considered as a starting point for the analyses. The analyses involve tracing back the cascade of representations that led to this composite document, and drawing on Latour (2005) to examine the work done by this planning document; in particular, how it becomes constituted through manifold representations and how the achievement of 'optical consistency' across such representations enables mobilizing allies. Data collection took a year and a half, and involved document studies, *in situ* visits, and interviews. The documentary data included public city plans, consultancy reports, memos, decision protocols, architectural drawings, pictures, movies, press releases, and articles from magazines and the local newspapers. *In situ visits* allowed for viewing how construction progressed. Interviews were conducted with 11 people, including the lead architect, and project manager.

Using data from these two contexts, we illustrate our ethnographic approach that allows the researcher to trace connections across complex engineering projects, reconstructing practices through their visual representations, and observing their effects. Table 1 compares the two cases.

In what follows, we describe how, in the case of Heathrow T5 roof sub-project, design concepts are worked out across a cascade of different media at different scales in practices that both take place locally around a physical model and are linked across localities through digital models and representations. Second, we describe how, in the case of the Turning Torso, the city plan brings together pictures, notations, and texts and how these interact with numerical representations as plans and budgets get used in design and in decision-making to manage the ongoing project process.

Heathrow T5 Roof – developing shared understandings of responsibility and risk

The idea of a central data repository at Heathrow Terminal 5 was introduced in recognition of the importance of representation and assurance of designs and assembly processes ahead of time. On an earlier project at Heathrow, the Heathrow Express, there had been a tunnel collapse at night, which revealed a lack of documentation and inadequate preparation. The project insurers, and project client BAA, were keen to ensure that Heathrow T5 was built according to the best practice. After interviewing the senior managers on the Heathrow T5 project, a closer focus was given to the T5 roof sub-project as this was described as an example of the success of this approach. Through interviews with the team it became apparent that on the roof sub-project, architects, engineers, construction managers, suppliers, and fabricators worked in an integrated team, had shared responsibility, and collaborated to solve problems. They enjoyed working on the roof sub-project.

Most of the modelling work on the Heathrow T5 roof sub-project was focused on decisions about how to

Table 1. Comparison of the two cases.

	Heathrow T5 roof sub-project	Turning Torso
Focus of illustration	Visual representations used to develop design and to articulate construction processes in the assembly manual	Malmö city plan, and its constitutive drawings and representations and their effects
Design decisions	The decisions made by the team on how to build the roof; the risk management approach, using a range of visual representations rather than/as well as the single model environment	The decisions made by the client and the Malmö city to build the Turning Torso. Increasing the radius at the base
'Paper-work'	Performed on the assembly manual used to coordinate the temporary and permanent works in the erection of the roof	Performed on the Malmö city plan used for stakeholder engagement with authorities
'Model-work'	'Model-work' offers a holistic view of the building as opposed to fragmented view on screen and drawings; physicality (seeing and touching sustains sensemaking of the building masses and structures); shaping, cross-checking, and testing design decisions by switching across models	The process of visualization creates new connections that translates drawings/'paper-work' in the project office into a physical scale mock-up/'model-work' for testing structural stability in a wind tunnel laboratory – and back – into test results, revised design drawings/more 'paper-work' at the project- and architectural offices.
Speed of change	There are digital and physical mock-ups that enable design decisions to be made at different rates – the plasticine models can be made quickly, while the detailed roof model relents the pace of work, but is essential when the team needs to engage to sense physicality and to 'test' drawings against matter	Project progress depends on visual representations, which facilitates further actions such as the (re)making of design decisions and project plans
Connections	Shifts in technologies of representations, from 2D drawings designed by the engineer, to 3D models on computer, to 4D models in plasticine and cardboard, to a full-scale prototype using real materials. These representations establish connections among participants, as well as in time (from design to construction) and space (from the office to the building site and off-site tests)	Malmö city plan is an example of how a visual display evolves and becomes a stabilized (reified) set of connections. It represents a set of connections across space and time, with six different dates, four different signatures, five different references to municipality representatives, the client and chief architect and representations of different scales

Figure 1. Computer screens and physical models.

design and build the roof. A key question in design was about getting to a node design that could be cast by the fabricator. A cascade of physical models, in wax, cardboard or plasticine, were used in exploring the options. The preliminary designs for nodes in the roof structure, which were made in plasticine, were photographed by the architects, and then the plasticine was re-used a number of times as the design evolved. The digital modeller worked alongside two physical model-builders who were also employed by the architect. He came to play a pivotal role in the team, not only in design but also in construction planning.

A photograph of the models in the design office (in Figure 1) shows how, pulling back from a focus on the screen, to examine the practices around the screen reveals the intertwining of digital and physical practices in play. The plasticine nodes and cardboard models are visible. When asked what he had learned on the project, the fabricator said 'The importance of physical models – that was definitely a bonus.' The chief engineer also emphasized the importance of having scale models in the workspace, including the one shown in Figure 1, saying that:

> In understanding what the 3-D shape actually looks like and how it looks through angles and that kind of thing, very useful indeed, because there are things, especially as geometry has become complex, it's fairly difficult to see very much at a time on the screen, your perception of the complex shape is … is quite limited, you have to make the thing move around and then you can't quite remember what was on the other side, and it's all a jumble because all the on the tower … you see on our models of it, you see the framing on this side of the building and then you also see the framing on the other side of the building and it makes you feel there's something physical in front of you, you can … you can perceive it more, it's sort of – it's there isn't it? – it's to do with the way we perceive things, so they were very useful.

Digital modelling was primarily the role of the digital modeller, who came with skills using a solid modelling package that became useful for considering the 3D shapes required for the abutments. The successful use of the digital model for these shapes led to his involvement in modelling half a bay of the structure (the entire structure was then duplicated out of this, so that there was no need to model it more than once). However, digital modelling was also used by the chief engineer who used a frame model in the structural analysis and wind testing of the structure. From the 2D drawings provided by the engineers, the fabricator built a digital 3D model of the steel structure. While data reformatting or re-inputting may sometimes be caused by unnecessary inefficiencies in the design processes; in this engineering project, they were often related to active cognition – a rethinking and working out of the structure.

The design team used multiple media to develop and test alternative solutions: physical cardboard and plasticine models, and digital models – solid models of nodes and joints in the structure, models from wind tunnel data, and a model of a roof bay. The focus was on systematically considering what could go wrong. An independent engineer was also employed to check all of the engineering calculations. He articulated the wider suspicion of digital solutions and their implicit assumptions:

> I think you have to step back and say, yes, it's very useful, but challenge it, constantly challenge what you see. Does it make sense? And have the ability to be able to get in and be able to check it. And that's the problem we find with third party software: you don't have the ability to get in and chase what you would like to check. So we tend to use our own.

Working under the pressures of a construction programme, work was separated and integrated through socio-technical rather than purely technological solutions. The team resisted pressure to discard its physical models and iterated across the cascade of different models to resolve issues that arose at different scales.

This cascade of models and artefacts extended not only throughout the design process, but also into construction planning with many of the sub-assemblies modelled and tested off-site, as shown in Figure 2. Half size models of details of the abutments were made at the casting foundry at Burton-on-Trent for the team to inspect. The largest of these tests occurred after the design had been fixed, with a full-scale prototype of half a bay built off-site in a field in Yorkshire in what became known as the abutment 'first-run study'. Through these and other contexts, knowledge of the

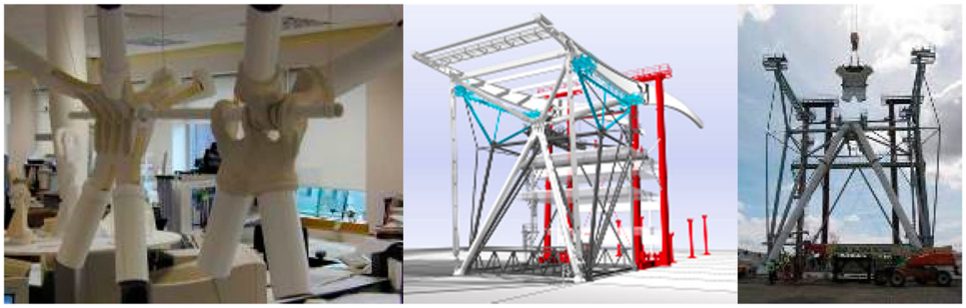

Figure 2. The cascade of representations, from the models in the office, to the digital model, and a full-scale prototype.

structure, its design, and its erection were developed through interactions across different types of models.

The use of such a large number of models draws our attention to the way that models enrol particular actors, and points to the importance of switching between models in generating design and decision options. The models used have different data-structures and affordances – some are homogeneous and easily pliable; others are more articulated and are at a scale at which they can be walked around. Digital models, which are viewed through the screen and rotated, are constructed in different formats, as solid models or as 2D vector frameworks. These objects are focal to the work and skills of different communities of actors, re-organizing social groups and creating different boundaries between practices.

The assembly manual, put together by the construction manager with responsibility for the raising of the roof, reveals several features of what Latour (1986) has termed inscriptions or 'paper-work' (p. 20). With more than 100 pages, the document brings together into the same place substantial explanatory text, more than 100 tables, charts, matrices and graphics, photographs, annotated models, plans, and sections, and links to further documents such as certificates. The 'controlled', up-to-date, version of the manual was digital, held in the shared electronic data management system, with copies printed for individual reference being seen as 'uncontrolled'. For each of the six lifts involved in raising the roof, engineering criteria for the lift had to be signed off by the relevant authorisers from across the supply chain (in a table on the front of the manual) before work proceeded. The manual was revised for each lift, with text in bold red showing specific and changed actions for the current lift.

This composite, hybrid, and rarefied document collated the outcomes of relevant earlier work, while making salient the decisions that had yet to be made and checked by the project team. The final of the six lifts took place in February 2005. There was a large team of engineers involved, with contact details for 19 key positions and 16 understudies involved in each lift, where the roof was designed to be assembled on the slab and then strand-jacked into place. The document summarized the best practices associated with each lift, combining charts of weather forecasts, photographs, views from the digital models, plans, and organizational charts. It contained the 3D images of a model that was developed to show the erection sequence to the project insurers. Yet issues that had already been resolved in the design process were not recorded in detail in the manual. Although there were pictures of the digital models, there were no images of the wax, cardboard, or plasticine used in evolving the design detail.

Turning Torso – negotiating design and decisions

Close examination of the Malmö city plan, shown in Figure 3, reveals the composite nature of the document and its role in mobilizing key stakeholders and decision-makers across time and space. The plan is made of paper and is both visual and mobile across time and space since it carries six different dates, four different signatures, and five different references to representatives from architecture, city planning, and the Malmö municipality, respectively.

In the plan, the scale of the inscriptions varies. For example, there is a horizontal scale 1:1000 that measures the size of the geographical space for the surroundings of the building. The scale is combined with a metric that depicts geographical North – together, they help to delimit, orient, and locate the construction site within this larger city geography that is named as the 'Western Harbour' (in the plan named 'Västra Hamnen'). Then, there is another vertical scale that, in combination with an architectural drawing, measures and summarizes the height of the tower's facade to be 179.01 m and the height of each of the nine cubes in the building structure to be 16.53 m. There are also texts and notations that explain and define the total maximum height to be 211 m (including extras on top such as antennas) and 196 m for the building construction. The building design visualized in the city plan is, in turn, a 2D translation

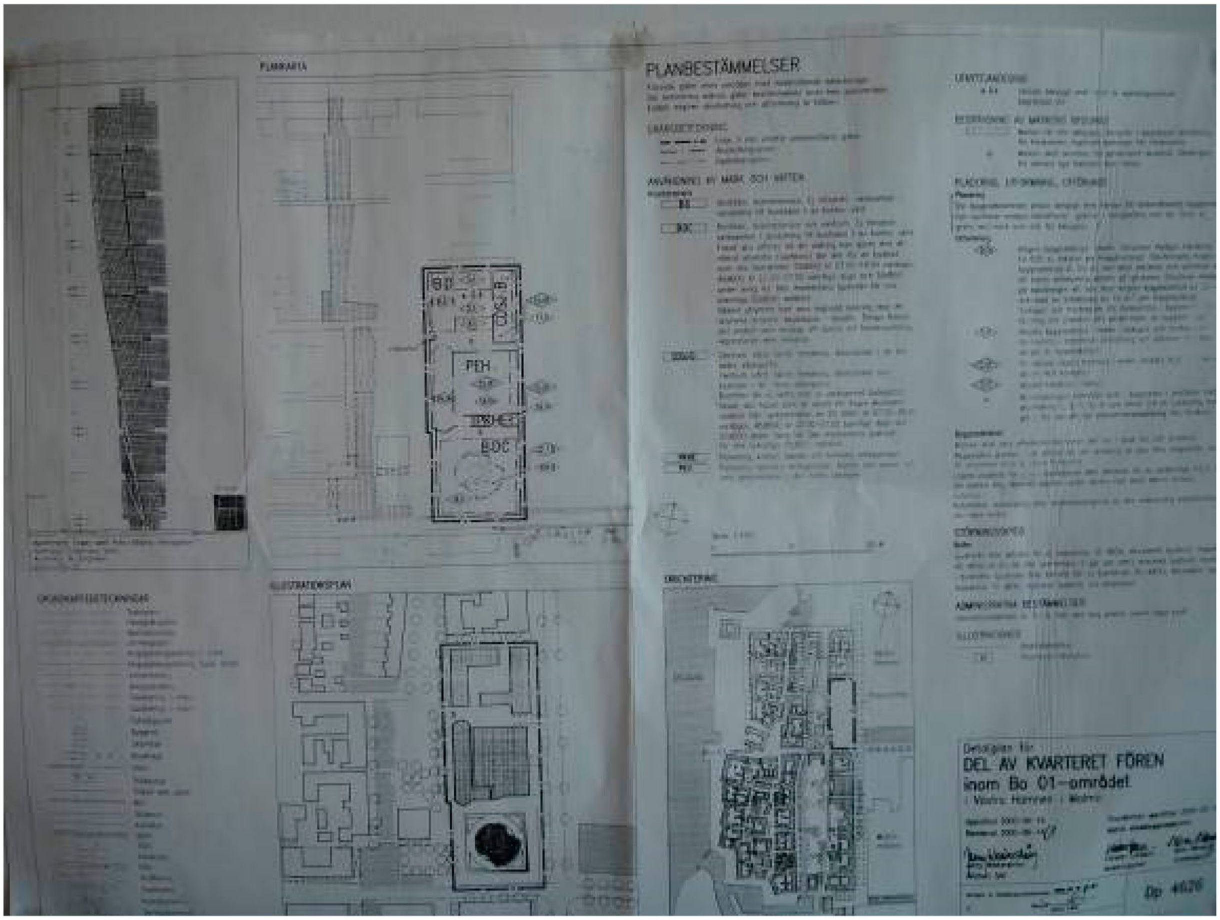

Figure 3. Malmö city plan. Source: Malmö city's public archive.

of an artistic three-dimensional (3D) physical sculpture that has served as a 'role model'.

The plan makes it possible to superimpose and link images (drawings of spaces, both built and natural such as the sea and coast line), notations and texts from different domains, such as architecture, geography, city planning, building codes and the law, the decision-makers of the city's municipality, and a private housing association that seeks the public approval for an apartment tower that resembles the one shown. It is due to the plan's 2D and hybrid features, combining images of space, notations, and written text on the same sheet of paper, that these links can be established.

As further noted by Latour (1986, p. 22) 'space on paper can be made continuous with three-dimensional space'. The result is that we can work on paper with rulers and numbers, but still manipulate 3D objects 'out there' (p. 22). It is a contingent, and therefore open empirical question if a plan on paper, the 'paper-work', can do more work and mobilize on a larger scale so as to be translated into a 3D object. For example, the private housing association might at some point in time cancel the plan due to a lack of money or interest, or the plan and request for a building permit might be interpreted as a significant violation of established building norms and be rejected by the city's public representatives and authorities. However, in this case the existing building norm was negotiated and adapted to the building project in the city plan when it was formally approved as a legal binding document in September 2000. The plan and document not only traces and summarizes a process of mobilization and decision-making for the building project, but is integral to this process. Thus, according to the head of city planning not any building and plan would do because

> the [shipyard's] crane was destined to be sold and sent away. The city's landmark was to be replaced by a new one, representing the transformation from an industrial city to the new area—Malmö, the city of knowledge and events. (Interview quote)

The city plan is but one in the midst of a cascade of visualizations that work to define and negotiate the existence of the emerging 3D object and building. The housing association was still trying to come to terms with their project when the new city plan was formally decided and approved. In order to reach a decision of whether to build or not, the board of the housing association requested more detailed calculations of the project's costs and revenues. Project management responded with a written memo that questioned the size of the commercial area and a proposal to increase the space in order to improve the project's revenue potential. New architectural drawings were produced in order to accommodate these new requirements and concerns. The commercial area was increased from 14.797 to 17.723 m^2. Due to these design changes, the budget depicting the project's total production cost was re-estimated from 550 to 728 M.SEK. When the board members gathered in December 2000, they were equipped with documents that visualized and described the project's new design, cost, and revenue potential. It was decided to build the Turning Torso accordingly.

Prior estimations and decisions concerning design and cost changed as the project was progressively elaborated with the help of revised architectural drawings and budgets. Initially, the architectural drawing – a visual representation – provided a point of reference, which allowed for calculations and estimations of what it would cost to build such a tower. A budget calculation (another visual representation) described and summarized the 550 M.SEK total production costs for the Turning Torso. Next, when the budget circulated among the board members and project managers, it gave rise to further questions and concerns about the project's revenue potential. A dynamic link between architectural drawings and budget was established when the former were revised in order to take into account the request for larger 'commercial' space. Once these commercial concerns were taken into account, the board was able to make their strategic decision to endorse the project. It seemed that in order to make strategic decisions, more 'paper-work' was required.

When the strategic decision was made, the building project was still far from reaching its final form. In order to become three dimensions and more real, more visualizations were required. About two months after the decision, the project team gathered on the construction site to discuss this question of how to build the Turning Torso. The structural checker was assigned the task of auditing the more refined and detailed drawings coming from the architectural office. During the meeting, he questioned the stability of the structural design. He considered that the building might be vertically unstable, especially under extreme wind pressure. The representative from the architect office was not immediately convinced about the stability issue. The meeting therefore resulted in a decision to submit the structural design to a test. Testing a building that does not yet exists as a 3D structure requires still more visualizations. The 2D drawings were deemed insufficient for this test. Instead, the project team decided that the building's structural design drawings had to be translated into a 3D small-scale mock-up. The advantage of a small-scale model is that of being much faster and cheaper to build and test compared to a full-scale one model. However, due to its artificial scale, the mock-up requires an artificial environment that is able to simulate a real natural environment with strong winds. Such an artificial environment is equipped with measurement instruments that can produce the data and facts needed to represent and show how the structure performs under extreme weather conditions. The mock-up was put into a wind tunnel test in a well-reputed laboratory at a Canadian university. The results from the test prompted the project team to revise previous design decisions. As the structural checker further explained, '[i]t took some time to get the results, but we had to make sure because it is important to have [the] architecture with us all along' (interview quote). Latour (1986) summarizes the main problem with this sort of detour as one of 'mobilization'. 'You have to go and come back *with* the 'things' if your moves are not to be wasted' (p. 7, italics in the original). When the laboratory returned with the results, it was decided to increase the radius at the base from 12 to 15 m, although, according to the structural checker, 'it could perhaps have been 1–1½ metre smaller, but this one [the first estimate of the radius], I do not think that would have been sufficient' (interview quote). The boundary of the zone between what is known and what is still uncertain could be drawn with more precision, thanks to the mobilization of the results from the wind tunnel test. Knowledge claims can be tested, new knowledge about the structural feasibility of the design can be produced, and a new design decision can be made. The architect office revised the architectural drawings according to the new design decision (Figure 4).

This was a strategic decision, which allowed the project to continue: Nobody could live with the uncertainty associated with an unstable Turning Torso. The project had also gained in value, thanks to the progressive elaboration and circulation of visual representations. The design decisions were made, unmade, and remade, with the 15-m radius of the base being eventually established as part of the design. Such making and unmaking of decisions should be regarded as an outcome of the dynamic process of visualization and knowledge production described above.

In August 2005, the city of Malmö celebrated the completed building. An international event in the form of a press conference took place at the 54th floor. But a critical question was posed to the chief architect and their team: 'How could you calculate with only 1700

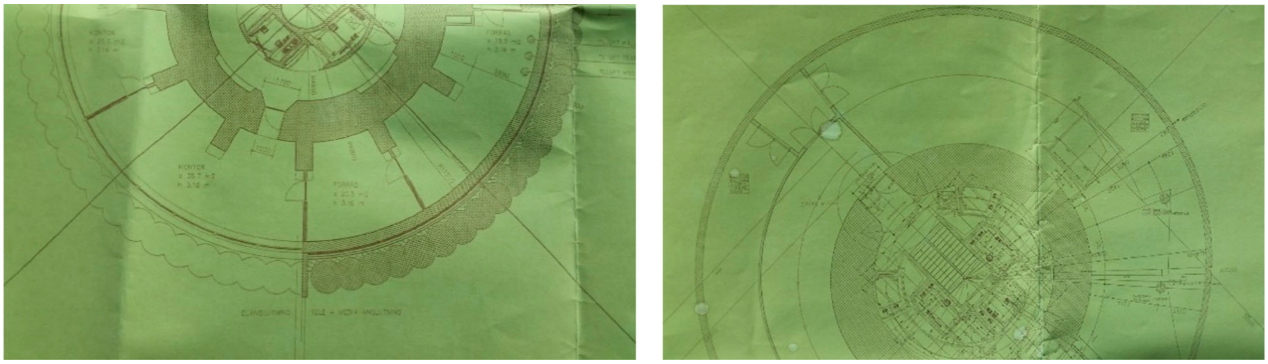

Figure 4. Design solution, left: prior to the mobilization of the wind tunnel test, dated January 5, 2001; and right: after the wind tunnel test, dated May 31, 2001. Source: Malmö city's public archive.

tons of steel when steel and even costs actually ended up with twice as much? How could you be so wrong?' Confronted with this question about the peculiar relationship between the calculations of steel and the delays and rising costs of the Turning Torso, the architect replied in a somewhat strained way:

> There is nothing wrong, and you are sitting here on the 54th floor. The building is very stable and solid. As an engineer I know that. If there were something wrong you would not be sitting here. It is also a beautiful building, and you have to understand that it is not one made according to standards. It is an innovative building.

The CEO of the housing association supported the architect by explaining, 'if anything was wrong, it was the first budget estimations that severely underestimated the costs of conducting such a project'. The comment by the CEO prompted another reply from the audience 'But if the budget had been correct in the first place, we would not be sitting here today, right?' The CEO replied, quite dryly: 'That is entirely correct.'

Concluding remarks: tracing connections using visual representations

By tracing connections through cascades of visual representations, we make a twofold contribution. First, through the discussion of these two studies, we offer an alternative approach that supplements situated ethnographies of design practices (e.g. Yaneva, 2009; Groleau, Demers *et al.*, 2012; Garreau, Mouricou *et al.*, 2015; Ewenstein and Whyte, 2009). Rather than assuming that action unfolds where the observation takes place (Czarniawska, 2007), our ethnographic approach allows the researcher to be nimble, tracing connections across engineering projects through visual representations. It differs from multi-sited ethnography (Marcus, 1995), in that it focuses on following visual representations, rather than individual actors. The rationale behind this choice of focus lies in an understanding that visual representations carry on themselves the results of manifold interactions among actors (Christensen, 2012; Nicolini, 2012).

The growth of digital research tools for capturing and analysing visual aspects of work have led to a recent focus on more micro-analyses using comprehensive approaches, such as video ethnography (e.g. LeBaron and Whittington, 2009; Smets *et al.*, 2014), which are increasingly used to capture and analyse substantial data about detailed interactions within specific places and times. Our contention is that it is also useful to use visual representations from the field to understand action at a distance. Interviews are used in our studies to retrospectively discuss the cascade of representations, but images from the field proved to be particularly useful as actors' sensemaking shifts over time. Differently from the retrospective accounts (and rationalizations) produced by actors, images carry a stable memory of the particular times and places in which they were made. As they circulate widely across sites, they bring aspects of particular points in the making of a design solution, and at the same time, they can be reinterpreted and recombined for other purposes.

The nature of each of the two studies reported here is different, with an entry at a different point in the process of project-based design. What the studies share is a desire to trace connections through the visual representations. In both cases, such work is iterative. However, in the Heathrow T5 case this narrative is largely constructed forwards, from the models to the assembly manual, while in the case of the Turning Torso, it is largely constructed backwards, from the city map back to the decisions made and the representations involved in the making of such decisions. These different research strategies allow exploration of different aspects of the cascading of visual representations. In the first case, tracing forwards made it easier to see what was *not* included in the consolidated cascade, with, for example, the plasticine models being omitted as they were no longer relevant to questions addressed in the assembly manual. In the second case, a particular strength of the strategy of tracing backwards was to identify controversies in the design, and to be able to interrogate how these had been resolved.

Second, a substantive contribution of this paper is in highlighting how connections may be traced forwards and backwards through the cascade of visual representations that plays a pivotal role in project-based design work. This contribution extends theorizing on the role of visual representations in project-based design (e.g. Luck, 2007; Sage and Dainty, 2012; Justesen and Mouritsen, 2009; Ewenstein and Whyte, 2009), drawing on Latour (1986) to show how interactions with a cascade of visual representations enable participants to develop and share understanding. In both the studies, visual representations were increasingly collated into and presented as a set of reified and hybrid forms through the design and project work. The assembly manual and city plan are examples of a 'consolidated cascade' that summarizes and presents a wider set of visualization practices. From different points of departure (the 'model-work' in the Heathrow T5 case and the 'paper-work' in the Turning Torso case), we observe the work of combining, editing, curating, and summarizing multiple sets of text, pictures, and notations by tracing connections through the cascade. Tracing connections provides insights into how designs are worked out across a cascade of different media and scales, and how pictures, notations, and texts interact with numerical representations as plans and budgets get used in projects.

Hence, there is an important practical lesson to be extracted from the cases and our analysis of the visual: to expect budgets, 2D drawings or 3D models to be 'correct in the first place' is to ignore their dynamic links and role in generating new valuable knowledge of what the building will look like and what it will cost, earn, and do. In the Turning Torso case, one can just imagine what could have happened to the project and outcome if everybody had maintained the design assumptions and decisions from December 2000, only to begin debating the stability issue at the world press conference close to delivery. Or worse, the building could even have fallen down if the integrity of the original design decision and plan had been retained. It is due to this interactive visual dynamics that the building's design and budget are revised and strategic decisions can be (re)made. Although the production of new knowledge is not obtained for free, it might more than offset the cost of such ignorance. There is also a theoretical implication concerning the dynamic relation between talk and visualizations. It is not just a coincidence that the talk at the conference focused on the budget rather than the building's design and stability. People talk about the important unresolved issues, but what becomes a particular important issue to talk about is articulated against a background of the other (stability) issues that have been resolved due to the progressive elaboration of the visual. The budget becomes the unresolved issue to talk about because it had to 'pay' for the building's stability.

Digital visualization technologies themselves are shifting the balance between 'paper-work' and 'model-work' and suggest new ways of designing and organizing. From the theoretical development in this paper, we anticipate, however, that the work of creating optical consistency that is discussed by Latour (1986) and observed in our cases will still need to be achieved. The process of mobilizing allies relies on the summarizing of a body of knowledge, and the implied depth of reasoning in the cascade of representations that has led to it. By drawing on Latour's work, we make a contribution to the recent literature on digital forms of visual representation (Justesen and Mouritsen, 2009; Whyte *et al.*, 2007; Dossick and Neff, 2011; Harty and Tryggestad, 2015). Our theorisation of this shift contrasts with that of Scheer (2014) in that it treats as an empirical question the extent to which any representation becomes used for exploration at depth or becomes a substitute for what it represents. While our focus has been mainly on models and drawings, we anticipate that digital transformation may change visualization practices by enabling greater use of simulations, as dynamic, rather than static, forms of representation.

This work suggests new directions for research to examine changing forms of 'model-work', 'paper-work', and consolidated cascades. For example, we envision that the mobilization of allies in BIM-enabled projects may be done through dashboards, with different digital layers, or interfaces that enable the body of knowledge in an integrated model to be abstracted and viewed from carefully selected viewpoints and which may themselves form a consolidated cascade. This technological complexity makes it hard to observe the effects of visual representation through situated studies that are limited to the design office. It makes it important to further consider the effects in other places, such as the construction site, to address questions such as how BIM either supplements or replaces more traditional design practices using physical models and with what effects across design offices and construction sites. As project-based design work becomes radically distributed across geographic areas, and difficult to observe (with for example much work also being done through a smartphone device), we suggest that the approach of tracing visual representations through the cascade is timely and important to addressing the kind of new research questions and practical challenges that arise because of the complexity of projects and their changing technologies of representation.

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