The 25th International Symposium
on Automation and Robotics in Construction

June 26–29, 2008

ISARC-2008

Institute of Internet and Intelligent Technologies
Vilnius Gediminas Technical University
Saulėtekio al. 11, 10223 Vilnius, Lithuania
http://www.isarc2008.vgtu.lt/

REACHING FOR THE SKIES: TIME AND TURBULENCE IN DIGITAL TECHNOLOGIES AND PRACTICES

Jennifer K. Whyte
School of Construction Management and Engineering, University of Reading
Whiteknights, PO Box 219
J.Whyte@reading.ac.uk

ABSTRACT

This research examines dynamics associated with new representational technologies in complex organizations through a study of the use of a Single Model Environment, prototyping and simulation tools in the mega-project to construct Terminal 5 at Heathrow Airport, London. The ambition of the client, BAA, was to change industrial practices reducing project costs and time to delivery through new contractual arrangements and new digitally-enabled collaborative ways of working. The research highlights changes over time and addresses two areas of 'turbulence' in the use of: 1) *technologies*, where there is a dynamic tension between desires to constantly improve, change and update digital technologies and the need to standardise practices, maintaining and defending the overall integrity of the system; and 2) *representations*, where dynamics result from the responsibilities and liabilities associated with sharing of digital representations and a lack of trust in the validity of data from other firms. These dynamics are tracked across three stages of this well-managed and innovative project and indicate the generic need to treat digital infrastructure as an ongoing strategic issue.

KEYWORDS

Digital infrastructure, time, technology, visual representations, organizational practices, coordination

1. INTRODUCTION

The uptake and use of new technology may alter existing and introduce new dynamics into organizations. The sequencing and pacing of every-day working practices has important consequences for efficiency and for the quality of outputs [1, 2]; hence there is growing theoretical interest in the temporal or dynamic nature of relationships between technologies and organizations [e.g. 3].

Large construction projects are a challenging organizational context with significant co-ordination challenges. Mega-projects, such as the Three Gorges Dam in China, the "Big Dig" in Boston, USA and the Channel Tunnel in Europe, involve distributed cognition across temporary coalitions of firms and individuals. Such projects are notoriously difficult and characterised by cost over-runs and delays [4]. Unlike in mass-production or process industries, in these settings organizational arrangements are also temporary. Though clear processes may be developed ahead of time, there is often considerable uncertainty that has to be resolved through ongoing practice, with little slack as each project and sub-project needs to deliver.

There has been considerable theoretical work on how individuals within such complex organizations resolve ambiguities and make sense of their experience. This suggests that structures and tools are vital to sensemaking and that when the structures and tools that people use to make sense of their position in the organization break down this can lead to a loss of overall sense-making [5].

A strong organizing vision may be required to maintain sense and motivate action around new information technologies [6]. Organizations that see the differentiation and integration of work as mechanistic may become unable to see how to do the work of innovation organization-wide [7], while those organizations that have a vivid image of value creation as a long-term working practice are more innovative. In them, people can make sense of their work, feel the responsibility for solving problems and can situate their solutions in their wider organizational context.

As new technologies for design, co-ordination and governance increasingly provide a digital infrastructure for delivery in such firms and projects, new questions arise regarding the dynamic processes associated with their uptake and use. In this paper I use a study of the mega-project to construct Heathrow Terminal 5 to address the research question: *What are the dynamic processes associated with new representational technologies in complex organizational settings?* There is considerable practical interest in centralizing information in construction [8] and this case provides a number of insights. The next two sections describe setting and method. Section 4 provides an overview of the findings; Sections 5-7 describe project stages and Section 8 draws conclusions.

2. SETTING: CONSTRUCTION OF HEATHROW TERMINAL 5

Imagine a project in which a building the size of eight football (soccer) pitches is to be constructed below a low radar ceiling and above a train station with severe limitations on vehicular access to the site. Though such constraints sound challenging enough, this is only a part of the £4.2bn (~$8bn) mega-project to construct a new airport terminal at London Heathrow: the work also involves the train station and connecting tunnels, a control tower and ground work for two satellites. The mega-project also involved a package of innovative procurement methods and approaches to project management which were introduced by BAA, in its role as the client, to deal with such constraints.

Construction work on the project, which was the largest in Europe, involved a concentrated effort to improve performance, and despite suffering opening problems the project was well run. The strategic approach taken on this project, Heathrow Terminal 5 (T5) reflects that of other large projects that were well executed. In their study of the construction of the Sydney Olympics, Pitsis, Clegg et al. [9] describe how a ‘future perfect’ strategy led to improved performance. They see this ‘future perfect’ strategy as involving clear forward-looking projection of ends and means for accomplishing them. As uncertainty extends beyond the planning phase, these projections exist as part of an emergent rather than explicitly scripted strategy. They are instilled in the shared values of the project.

To align everyone working on the T5 site to the same vision for the project there was an internal campaign on "History in the Making". Here, managers sought to instil core values: ‘*Making T5 safe*’; ‘*Making T5 quality*’; ‘*Making T5 within budget’*; ‘*Making T5 bang on target*’. This provided a carefully scripted shared narrative about the project to make everyone – operators, drivers, catering staff, engineers, technicians and managers – feel a part of it. The mechanisms for delivering the project include a new approach to managing the logistics of delivering goods, services and people and the ‘T5 Agreement’ an innovative collaborative arrangement to work with the supply chain and avoid getting embroiled in the litigious culture of the general construction industry.

As part of this overall strategy, a new approach was taken to the use of digital technologies on the project, through the introduction of a Single Model

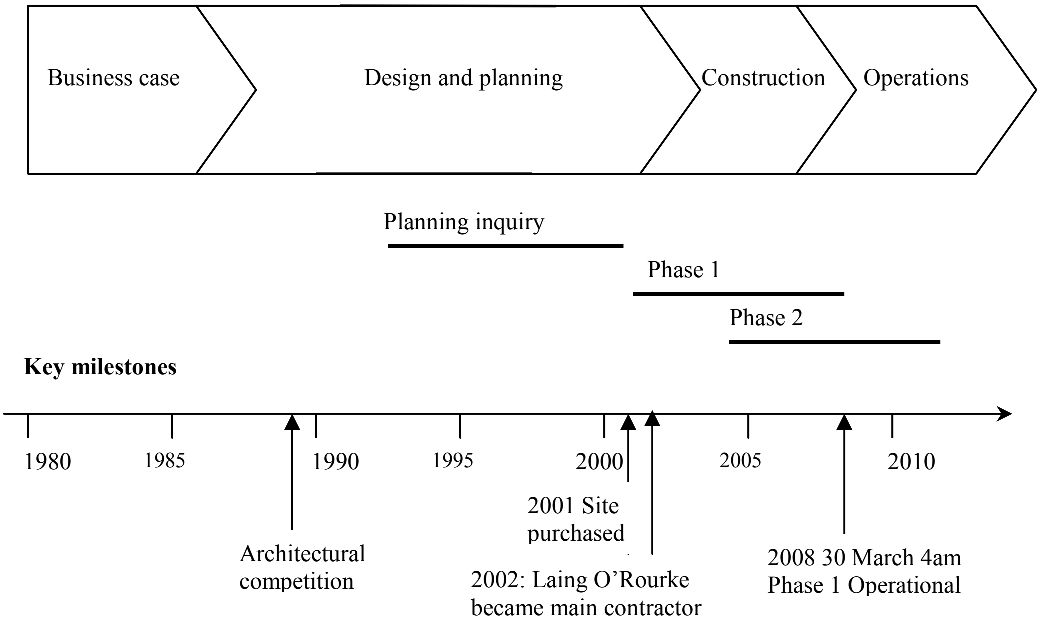

Figure 1 The timescale for the design and construction of Heathrow T5

Environment. This common data repository holds all.of the signed-off digital design data relating to the overall project. It allows for co-ordination between sub-projects, as well as providing a digital model of the facility that can be used throughout the life-cycle. Without such digital technologies, it is hard to imagine design, production and management of complex facilities of this scale and complexity

Use of the Single Model Environment has been the focus of previous research, with Harty conducting an ethnographic study of its use in detailed design work between October 2002 and June 2003 [10]. In this paper we consider the dynamics of technologies and practices across the life of the project.

Design and construction of Heathrow Terminal 5 has taken nearly 30 years, from the business case for the terminal developed in the 1980s, through the planning inquiry in the 1990s and the construction work in the 2000s. An overall timescale for the design and construction of Heathrow Terminal 5 is shown in Figure 1. Work progressed across the 16 major projects and 147 sub-projects. Construction was split into two main phases: Phase 1 includes T5A - the main terminal building, a new air traffic control tower, satellite building and additional aircraft stands (started September 2002, hand-over March 2008); and T5B which provides a satellite. Phase 2 consists of T5C, which provides another satellite (hand-over date of 2011).

The historical context is of crucial importance in analysing projects [11]. With John Egan as its Chief

Executive in the 1990s, BAA was seeking to improve performance, learning lessons from other sectors and from lean approaches to construction. John Egan came from the automotive industry and was involved in a UK initiative to 'rethink construction' [12].

The main contractor Laing had over-stretched itself on the Severn Bridge project and was merged with O'Rourke in 2002 to form a new company Laing O'Rourke under Ray O'Rourke's ownership. This change to the management of the major contractor brought a different dynamic to the project, with

Collaboration and governance tools

- A *Single Model Environment* (SME) or common data repository, for version control and controlling the data-set.
- The SME consists of a web-based system containing:
    - 2D and 3D design information;
    - Scheduling information;
    - Document management;
- Technologies include Documentum, CITRIX and AutoCAD ADT.

Product modelling tools

- *Digital Prototyping*: detailed 3D models of components or assemblies
- *Visual Methods statements*: 2D print-outs of 3D models, with construction information

Process modelling tools

- *Project-flow*: scheduling of daily activities that allows information on performance to be generated

Figure 2 Types of digital technologies used on Heathrow T5 in 2005 and 2006

changes to the business processes and technologies used. Changes in leadership at BAA also brought changes, with a new project director in 2002.

The construction of the project pioneered innovative working methods [13]. Particularly important precedents for the delivery of Heathrow T5 include large UK and international construction projects such as Hong Kong airport, the Glaxo building at Stevenage, UK and the Heathrow Express rail-link. The main lessons that were brought from these projects included the benefits of a prefabrication strategy with accurate documentation.

3. RESEARCH METHOD

This research is based on in-depth qualitative research involving five colleagues conducting interviews on Heathrow Terminal 5. Following the initial conversations and a site visit with the main construction contractor, Laing O'Rourke, a high-level set up meeting took place with Directors from Laing O'Rourke and the BAA Project Directors. At the time of this meeting, in October 2005, construction was at its busiest point on the site and the two BAA Directors we met had responsibility for £4.5m-a-day of construction work on site.

The overall research had two themes: integrated team work, and digital technologies. Hence our first interviews focused on integrated working and learning before, during and after the project, and included questions about the use of digital technologies. These interviews were conducted with key individuals within BAA, and Laing O'Rourke between November 2005 and May 2006.

Later, I conducted interviews focused on collecting more detailed information about the use of digital technologies on the project. In this work, I sat in on meetings to discuss the use of software and was given demonstrations of the tools involved. As I started to analyse the data I found places in which further clarification was needed. I decided to look in more detail at one sub-project that was highlighted as an example of good practice: the T5 Roof sub-project. In this context I conducted additional interviews with a wider range of stakeholders between January 2006 and November 2006.

I was personally involved in more than 80 face-to-face interactions in 2005 and 2006. In this paper I use this data-set to focus particularly on questions about technologies and practices.

4. OVERVIEW OF TECHNOLOGIES AND PRACTICES

Figure 2 shows technologies that were in use when I conducted field research in 2005 and 2006. The data highlight changes over time and two areas of turbulence in the use of technologies and representations. First, there is a dynamic tension

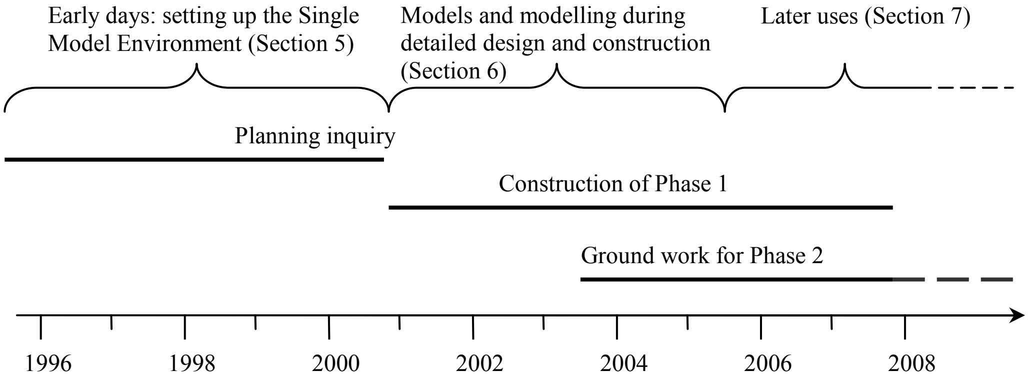

Figure 3. Three periods in the use of digital technologies at Heathrow Terminal 5

between desires to constantly improve, change and update these digital technologies and the need to maintain and defend the overall integrity of technological systems and organizational processes. This is illustrated by the constant problem of people wanting to add to the digital infrastructure. An IT manager noted that:

> *The killer for us was people would come in with bits of software and say oh, we've got this piece of software, you haven't got anything like that on T5 and this is what we are doing.*

Second, the temporal processes of updating the model introduce dynamic instabilities, with sign-off processes introducing delays and validity issues. There were concerns that information in the Single Model Environment was assumed to be correct without being verified.

> *So we figured out, well hang on, this thing's next to useless to us, to actually making anything. It might be of some use for visualising, but next to useless in terms of making anything, because it doesn't fit. It fudges stuff.*

Use of a Single Model Environment had top management support, however there was nothing like the 'History in the Making' campaign to bind participants and provides a guide to practice. The lack of a simple shared vision for the single model was a source of consternation to the system builders, who ask:

> *How do you get people to use it, how do you get everybody working with a single thought and working within a single methodology?*

Though there was extensive documentation and training the system was not used as the system builders intended. This was not seen as a technological issue:

> *This isn't about the technology, it's about the processes and managing the people to use the technology properly for everyone's benefit.*

The approach to co-ordination lacked a strong shared vision and hence had a strong emphasis on formal procedure which made it particularly 'brittle.' When

failures occur within the system these propagated through the system and the whole system came to be considered as failing. Use of these technologies varied across over the life of the mega-project as well as across the various sub-projects. At the point when we studied the project, the Single Model Environment was less in evidence on site than a variety of product modelling and process modelling tools.

To put the use of digital technologies on the project into a historical context, I crudely characterise three periods as shown in Figure 3.

In the next section, I consider the early days, when the Single Model Environment was being set up (1996-2001).

- In Section 6, I consider the period when there was significant work on site and when models and modelling were being used during detailed design and construction (2001-2005).
- In Section 7, I consider the later uses from 2005 onwards, the period in which the observations took place, and in which T5C was on site.

The discussion of these periods illustrates how technologies and practices fragment and diverge due to the two areas of turbulence identified above and how work is then required to realign technologies and practices.

5. SETTING UP THE SINGLE MODEL ENVIRONMENT (1996-2001)

What became known as the Single-Model Environment (SME) is not a digital model – it does not necessarily contain a 3D model of the facility, but it is rather a common data environment which is used for version control for all of the digital data relating to the project. The ambition of the client, BAA, was to change industrial practices reducing project costs and time to delivery through new contractual arrangements and new digitally-enabled collaborative ways of working. The vision was laid out in BAA's IT strategy document in 1998 as:

capturing the volume of information in a way that was manageable;

- controlling change; and
- assisting life-cost implications (including maintenance).

The aim was to do this with software tools for managing workflow capability; as well as common CAD environment, planning and financial management tools. There are a number of models owned by different stakeholders that are used to generate the information that is then verified and shared through this single model. The idea is to update the model following construction so that following design and trades could use this information.

5.1. Defining this vision

There was a concerted effort to create and maintain this environment on the Heathrow Terminal 5 project. BAA brought prior knowledge and experience of using digital tools to the project. On a previous project, the Heathrow Express rail link, a tunnel collapsed in the night during construction in 1994 and so there was suddenly a need to provide high quality documentation. For both Laing and BAA, this incident was a particular stimulus to developing integrated working in the run-up to T5.

In 1996, a team was assembled to develop the required standards. From 1997, the work of this team was managed by a consulting firm and the team included the software provider. The work was motivated by the idea of sharing data and only generating appropriate information. It was organized around two technical solutions – a Single Model Environment and a project information system. One of the engineers that put CAD systems into place on the Heathrow Express project following the tunnel collapse later worked as part of this team setting up the Single Model Environment on T5. The team thought they had two years to deliver these as there was uncertainty about when they were going to site, and there was always the pressure to deliver on a short timeframe. During this period a set of high-level processes were developed. These included standards and methods for organizing digital data, and protocols for sharing that data.

> *And this is where the thing about the Single Model Environment actually came about. It had nothing to do with 3D modelling. It was a model environment, a single source of information [...] So that was the real basis of it, was central repository for all the information, signed off, fully controlled, so that only the latest, signed off information fit for use was accessible by all other teams.* [early system builder]

The team accepted that most of the CAD staff and many of the engineering or design staff would be contract workers who were not aware of the practices of their firms. They established a training school to train the whole workforce to produce 3D models and to teach them about the benefits of the Single Model Environment and the savings for them and their firms.

The job of the team came to an end when everything was built, they had specified and procured the software, done the proof of concept which ran for six months, tested it all out and found that it worked.

> *by about '98 we were signed off the project because they thought they had everything they needed, we'd set up the enabling teams, the training was going, they brought in their own CAD manager, and so we as the consultants, they said we don't need you anymore, thanks very much, great job, see you, and we went back to our own offices.* [early system builder]

The software provider worked with the CAD manager to implement the system and the original team disbanded and went back to the consultancies that they worked for, in which they worked on other projects.

5.2. Making the single model work

However the system that they built did not stay in use as they had intended it for very long. There was a protracted time period from 1996 to 2002 when the public inquiry was ongoing and staff were waiting to start work on construction. Desires to improve, change and update technologies lead to fragmentation with the introduction of untested ways of working. Some of the original consultants went back into the project to audit the Single Model Environment in 2000 and developed plans to re-engage the teams and get them to agree to the methodology:

> *we went down and audited it and basically what we had put in place had disappeared in the two-year period. Not totally, but the documentation had been changed completely, [...] So we set up the training schools, we rewrote the documentation, we engaged once again with all of the stakeholders down there, all of the different design offices, CAD managers and people like that, pulled them all in.* [early system builder]

During this period, the team of system builders encountered a number of unexpected problems with training and skills; and with the technology itself. The training of engineers became more of an ongoing process than had originally been envisioned. There was the need to engage and convince people of the importance of the new way of working. There was no obligation on them to work in this way, so persuading them took a considerable amount of effort. Also there were always new members of staff arriving, so this was not something that could be done only once but became an ongoing process.

There were also problems with the ability of the technology to deliver the vision. For example, the project information system that was procured was seen as robust as it was used by insurance companies to manage large quantities of information. It was believed to have been used by large project management firms to manage CAD data, although this later turned out not to be the case. As work progressed on the project, this information system became seen as too cumbersome by the engineers. It was often circumvented, and usually referred to by a derogatory nick name.

The extended timescale for this design stage of the project brought drawbacks – in particular a number of key champions of this approach left. Fresh ideas came into the project as new people arrived but the changes were also a barrier to learning from earlier experiences within the life of the project. Had one or more of the original designers of the system been retained they could have explained the rationale for decisions that had been taken earlier in the project and provided better links through the process.

6. MODELLING IN DETAIL DESIGN AND CONSTRUCTION (2001-2005)

At the detail design and construction stages, technologies and practices fragmented and diverged significantly. The model was largely used for reference and across the sub-projects there were concerns about the validity, accessibility and ownership of data within the model as processes to ensure information would be valid and spatially coordinated were not used. This section explores why.

This was the stage in the project that was observed in a previous study [10, 14] in which various sub-teams were building systems to integrate the work into their local practices. In their study, Harty and Araujo [14] describe how in the building services team, the commitment to integrating all design work into the 3D model led to protracted negotiations, during which time no design work was conducted.

Eventually the team brought in their own computer and software in which they did their work unofficially.

Within the supply chain, other efforts at digital modelling emerged alongside the Single Model Environment to cover the 'nuts and bolts' detail that was necessary for design, production and assembly of particular elements.

6.1. Critical interfaces and the single model

As the Single Model Environment became used on T5, it became seen as useful for macro-level co-ordination of space layout and planning. There were difficulties getting design data input into appropriate formats. The software and hardware available on site was inadequate to deliver BAA's ambition. Practical implementation was considered an issue of design management rather than (whole) project management. The environment reverted became used as a *drawing* standard rather than a *design* standard.

Much of the work with digital tools and technologies on T5 was not done directly within the Single Model Environment. Those with experience of the oil and gas industry noted that in phase 1 the use of the Single Model Environment was remote, for example:

> *we interfaced with the Single Model Environment really by taking the fundamentality of the building from that environment, designing, and then integrating it back in. So you took things out and then reintroduced things back into that environment so others could see exactly what you were doing. And that process was controlled, was a managed process. […] But it didn't operate as a PDMS environment [an integrated product model used in oil and gas], it was sort of remote and then reintegrated back into it.* [project engineer]

The functionality of the technological system was hampered by the eclectic mix of technologies used. The content management technology did not work particularly well with CAD drawing files, and these are instead stored on two shared server drives, one for working drawings, and one for the released drawings. There was also mixture of 3D and 2D modelling. This hampered the functioning of the Single Model Environment, because as soon as (second tier) suppliers started making 2D models on the basis of 3D information, reintegration of those models into the Single Model Environment was made impossible. In some cases, intermediaries (CAD designers) were put in place to translate/convert the as built drawings or as built survey provided by suppliers into the 3D model.

The computer skills of engineers and designers were an issue. One of the reasons it was not possible to get 100% compliance was the lack of capability in the industry:

> *When you need 1,200 designers, guess what? You can't get 1,200 designers in the UK construction industry […] because it just doesn't exist. Nobody comes, you know, pre-equipped with that level of capability. So what you end up having to do there is risk assess, in a way, in terms of how do you differentiate where the high value add, high risk design is, as opposed to the lower level detailing and everything that sits in between. So we've got all sorts of different CAD operators coming through different organisations to sit within these integrated teams.* [top project manager]

Many of the CAD designers employed on T5 later on had come from other industries. The software used in the original Single Model Environment had to be downgraded to match capability of designers, and use became locally organised, per sub-project, with success depending on factors such as the complexity of the work, the level of capability of people in the team and their behavioural attitudes towards integrated team-working.

6.2. Validity, accessibility and ownership

It was, ironically, the same set of motives that drove development of the Single Model Environment – the idea of sharing valid data; and the idea of only generating appropriate information – that led some engineers to avoid using it. In their daily work practices, engineers and designers found that the data they needed was not available or not reliable, and they worried that they were being asked to generate data that would not be used. One engineer said: *'you just don't know how difficult it is to find information there.'* Once the accuracy of data in the Single Model Environment was challenged it was difficult for engineers on sub-projects to trust that data, particularly where they wanted to pre-assemble components off-site:

What we realised was that if you look under the quality SME, it wasn't a very nice picture. So we had to do something different. If we were going in a pre-assembly strategy, you've got to be damn sure when that stuff hits site it's going to fit, otherwise you're in deep shit. Now it's a lot worse than in situ, with budget. If you're having to break stuff apart and remake it or scrap it, or do whatever. So we went looking for tools that were more production driven [project engineer]

One other thing that was not foreseen was that some occupational communities might not have the trained staff to use the Single Model Environment, or that there might be a lack of computer tools to allow them to plug their work into it. Harty and Araujo [14] described the problems faced by the building services community, and these issues came up in the interviews I conducted as well. This is a structural engineer, talking about the interface with the building services team:

that team was not 3D [laughs] specifically, so it took us a long time to get any information from them at all. Mainly because we didn't want to own the information by joining the pipes for them and even when they did give us 3D information it was using a programme called CAD Duct, I think it was, which is incompatible with the programme that we were using [...] so we had to, basically, trace tube over their tube [laughs], quite literally, to actually get, at least, a visualisation of the penetration of their structure. It was fine for what we were doing, I guess, [...] it caused a bit of pain that we had to wait quite a while to get that information off them ... [project engineer]

One of the issues here is the sheer scale of the project, and the number of different occupational communities that data needs to be translated across:

But, my understanding is for Terminal Five, and that kind of size of the project it's just too big, and is very difficult to use this, and it's literally that, it's just too big, and unusable as such really.[modeller]

Though the roof sub-project was a great example of the integrated team, I did not find a project that was using the Single Model Environment in the way that had been intended by the system builders. The engineers on the roof sub-project did not use the Single Model Environment extensively in their work. Modelling and simulation technologies were used, but the models were used for prototyping solutions rather than interfacing with other teams.

7. LATER USES (2005-)

In the later stages of the project, I found varying practices with a small centralised visualization team and the engineers involved in fit-out on T5A, and the engineers working on T5C. There were desires to constantly improve, change and update the digital technologies on the project. Individual firms sought to introduce their own tools and ways of working as they see digital modelling techniques providing competitive advantage in bidding for new projects. The team in charge of implementing the Single Model Environment made a number of modifications to the system.

7.1. Visualization and fit-out

In early 2005 a small centralized visualization group was formed in BAA with 3-4 modellers. They conducted an audit of the Single Model Environment on Phase 1 which was then at the fit-out stage. The sheer quantity of data in the CAD models available in the Single Model Environment made it hard to use the 3D information, so when the model was audited it was not even possible to view a section through the building using the available hardware. To navigate the model it had to be divided into very small pieces, each showing small sections of the overall project. The model has been changed to make it easier to access relevant data and the team produces a weekly visualization report, showing the current scope of work, the aspiration, and the data in the Single Model Environment.

A visualization company was paid to create visualizations from the 3D model. Other work that had originally been developed in 3D was also added into the Single Model Environment in 3D. At this stage it was felt easier to input and use information, as most of the design and construction work has been done and there are not so many issues with version control:

Because it's the end of the project now, so the most work is done, and all the information is being released now, so you don't have that much information that is like developed a lot more now than it was before, so that's different. [...] But actually, till about maybe two *years ago, I actually don't remember pretty much anybody using it.* [modeller]

7.2. New practices on T5C

I looked at practice in phase 2 in particular detail. Here modelling was focused on the groundwork for a new satellite building as part of the construction of Terminal 5C. This is seen by management in T5 as an exemplar project taking learning from earlier phases of the work. Product modelling tools, such as digital prototyping of components and assemblies, or the creation of visual methods statements were being used in conjunction with process modelling tools to manage the construction process.

On T5C, part of the second phase, everything was modelled in 3D from the start. The visualization group were involved in setting up the use of modelling in the feasibility phase on Phase 2. As well as using the Single Model Environment and related technologies, here Laing O'Rourke has also developed new ways of using a number of product modelling and process modelling tools, which are also shown in Figure 2.

A question arises – why introduce new tools? The product and process tools introduced are used to manage component design and construction sequences and were developed in collaboration with a consultancy in the USA. For the team, the use of product models, such as digital prototyping and visual method statements was very closely associated with the desire to provide sub assemblies for the concrete reinforcements rather than introducing loose bars of steel. Prototypes were built for the purpose of getting rid of errors and difficulties in the assembly. Assembly requirements and the need to get those represented in the reinforcement design drawings from the start, was a main driver for work with the model. Laing O'Rourke focused the modelling effort on areas where there was a lot of repetition, so they would look to recover the investment through driving labour costs down (less operatives doing sub assemblies on site) and productivity up. Visual methods statements were developed for particularly complex designs.

The use of 3D was felt to be good for getting an overview of the work. For the operatives on site, visual methods statements and other graphical information are used to explain the design. One of the engineers commented:

> *the big coup with this, is I've literally sat down, and within the first week of being on the job, I felt as if I sort of knew the job to a certain extent. Whereas traditionally, if I just had a load of CAD IC drawings, I'd be there for probably a month before I had the same depth of knowledge.* [project engineer]

Models are useful in reworking the design and ensuring its constructability on site. However, the need to be more strategic about the application of resource to developing 3D models was also evident. Some components and interfaces are modelled in detail in 3D and then these models are used to generate many drawings showing different views. Although some of this 3D modelling is useful for prefabrication, in some cases the additional drawings that are being generated are not useful to the engineers working at site. According to one engineer sometimes the additional work that is done to show details in 3D doesn't add value.

Process modelling tools can play a role in the management of interdependencies or interfaces. It can underpin integrated team working by allowing more parties to the work to make their knowledge and the constraints that are present in their working schedule visible and thus apparent to others. By providing the data to track actual practices, and compare these with the projected work patterns. It has been invaluable in driving up productivity. On a T5 Project Data Sheet created by Laing O'Rourke to disseminate lessons learnt internally, the example given is of the T5A structures team in which:

> *although the average number of people in the team has stayed constant, the team has increased the number of tasks it is committing to from under 10 to over 40. This increase has occurred over a period of a year and a half. During this time their PPC has increased from an average of 72% to 89% and has only dipped below 60% 3 times in 77 weeks* [T5 project data sheet]

The process modelling software also allowed for data to be collected on why people don't meet targets, and this has provided some interesting results, showing for example, that non-completion is much more likely to be because of a change in directive than bad weather at site.

8. DISCUSSION AND CONCLUSIONS

These findings highlight changes over time associated with new representational technologies and indicate the need for digital infrastructure to be treated as an ongoing strategic issue by managers in complex and changing organizations.

In particular, they draw attention to two areas of turbulence in relation to technologies and representations:

1. *technologies* – a dynamic tension between desires to constantly improve, change and update digital technologies and the need to standardise practices, maintaining and defending the overall integrity of the field; and
2. *representations* – dynamics result from the responsibilities and liabilities associated with sharing digital representations and a lack of trust of the validity of data from other firms.

The area of turbulence associated with *technologies* can be addressed by reducing the value of novelty to individual stakeholders. Introducing a new innovation into a major project provides significant reputational benefits to individuals, consultants and firms, which are not accrued by faithfully following standard practices. To reduce this area of turbulence, managers need to increase the symbolic value of collaborative practice.

The area of turbulence associated with *representations* can be addressed through detailed attention to the processes of sense-making within different phases of delivery. Organizations are vulnerable to breakdowns in sense-making when they change and update technologies. Distributions of responsibilities and liabilities and the lack of trust in the validity of the data mean that representations available through the central database are not used or updated. To reduce this area of turbulence, managers need to articulate contractual responsibilities clearly and also to pay detailed attention to the sequencing of updates to a shared model and to manage this as an ongoing strategic issue.

A practical implication of the research is the need for a strong organizational vision [7,8,12] associated with technology and to get the buy in of the various stakeholders to that vision. An attempt was made to do this at Heathrow T5. Top managers, and those involved in the development of technological systems to support innovation processes on large-scale capital goods and infrastructure projects need to create an image of organizing that can help professionals to make sense of the Single Model Environment as a standard across the large project, along with clear responsibilities for its delivery. The data suggest that if the focus is solely on technologies, standards and processes then there is not a sufficiently vivid image of value creation to sustain the innovation. Technology champions can experience fatigue, in constant attempts to change the 'status quo' where permanent and contract staff turnover is high.

This image or vision must be flexible enough to allow for the use of the technology in ways and in circumstances that the system builders had not foreseen as long as these uses support the overall vision or can be made to cohere to the overall vision. The future perfect strategy [9] provides a useful template for what such an image of organizing might look like, and the success of the 'History in the Making' programme provides another example of how a large overall vision can provide a useful guide to sensemaking and action in relation to digital infrastructure.

This research contributes to ongoing theoretical debates about the dynamic relationships between technologies and organizations. It suggests new areas for research – to better understand the turbulence associated with new technologies and practices.

9. ACKNOWLEDGEMENTS

I would like to acknowledge the expertise of people I talked with at Heathrow Terminal 5 and the various inputs of colleagues involved in the research: Tim Brady, Catelijne Coopmans, Andrew Davies and David Gann. I would also like to thank Sunila Lobo for her comments on the paper. I gratefully acknowledge the support of the EPSRC through the Innovation Studies Centre at Imperial College and the Innovative Construction Research Centre at the University of Reading.

REFERENCES

[1] Perlow, L. (1999).The time famine: toward a sociology of work time. *Administrative Science Quarterly*, Vol. 44, No. 1, 57-81.

[2] Perlow, L.A., Okhuysen, G.A., & Repenning, N.P. (2002).The speed trap: exploring the relationship between decision making and temporal context. *Academy of Management Journal*, Vol. 45, No. 5, 931-955.

[3] Orlikowski, W.J. & Yates, J. (2002).It's About Time: Temporal Structuring in Organizations. *Organization Science*, Vol. 13, No. 6, 684-701.

[4] Flyvbjerg, B., Bruzelius, N., & Rothengatter, W., (2003), *Megaprojects and risk: an anatomy of ambition*. Cambridge: Cambridge University Press.

[5] Weick, K.E. (1993).The collapse of sensemaking in organizations: the Mann Gulch disaster. *Administrative Science Quarterly*, Vol. 38, No. 4, 628-652.

[6] Swanson, E.B. & Ramiller, N.C. (1997).The organizing vision in information systems innovation. *Organization Science*, Vol. 8, No. 5, 458-474.

[7] Dougherty, D. (2001).Reimagining the Differentiation and Integration of Work for Sustained Product Innovation. *Organization science*, Vol. 12, No. 5, 612.

[8] Eastman, C., Teicholz, P., Sacks, R., & Liston, K., (2008), *Building Information Modeling Handbook*: Wiley.

[9] Pitsis, T.S., Clegg, S.R., Marosszeky, M., & Rura-Pouey, T. (2003).Constructing the Olympic Dream: A Future Perfect Strategy of Project Management. *Organization Science*, Vol. 14, No. 5, 574-590.

[10] Harty, C. (2005).Innovation in construction: a sociology of technology approach. *Building Research & Information*, Vol. 33, No. 6, 512 - 522.

[11] Engwall, M. (2003).No project is an island: linking projects to history and context. *Research Policy*, Vol. 32, No. 5, 789-808.

[12] Egan, J. (1998),*Rethinking construction*, Department of the Environment, Transport and the Regions: London.

[13] Davies, A., Gann, D., & Douglas, T. (submitted).The Sweet Spot of Project Success: Innovation and Learning at Heathrow Terminal 5. *Californian Management Review*, Vol. No.

[14] Harty, C. & Araujo, L. (2005). Aligning user practices in innovation: the case of Heathrow's Terminal 5 project. in Using Technology. Oslo, October 28-30.