Megaprojects as niches of sociotechnical transitions: The case of digitalization in UK construction

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Abstract

Transitions are processes of systemic change where niches peripheral to a sociotechnical regime accumulate momentum, scale up and eventually transform its core. In contrast to this dominant narrative in transitions research, infrastructure systems exhibit the reverse process as change propagates from the regime core to its periphery. We explore this under-researched process in the case of digitalization in UK construction. We analyse six UK megaprojects that span more than 30 years and show how the adoption of digital technologies that is driven by regime incumbents, seeds the processes of technology adaptation, aggregation, and system transformation. The adoption of digital technologies by incumbents is necessary to cope with megaproject scale and scope. Their adaptation to technology instigates organizational level change that starts at the regime core, accumulates with each project and makes these changes ripple across the industry and transform it.

Keywords: aggregation, sociotechnical transitions, megaprojects, infrastructure, digital

1 Introduction

Sociotechnical transitions are evolutionary processes of systemic change that alternate between stability and change (Geels et al., 2017; Markard et al., 2012; Smith et al., 2010). Their study has developed into a substantial research program (Köhler et al., 2019), where the central narrative is that a diverse set of radical innovations emerges in protected niches and their development along different directions has eventually some system wide impact (Geels and Raven, 2006; Geels and Schot, 2007; Kemp et al., 1998; Raven and Geels, 2010; Schot and Geels, 2008, 2007; Smith and Raven, 2012). In their development trajectory, sociotechnical niches enter progressively larger market segments and may fundamentally transform sociotechnical systems, i.e. legacy technologies, incumbent actor and the core rules of the regime that underlies system stability and reproduction (Fuenfschilling and Truffer, 2014; Geels, 2011).

Underlying this conceptualisation of system change, is the notion that it proceeds mostly from peripheral niches, or other regimes, to the regime core (Fuenfschilling and Truffer, 2014). The implication is that small scale options have received far more attention than large scale technological options in transitions literature (Kanger et al., 2020; Sovacool and Geels, 2021; Turnheim and Geels, 2019). Nevertheless, infrastructure systems delivered through megaprojects can also be important for transitions (Sovacool and Geels, 2021). Megaprojects, generally cost more than US$ 1 billion (Flyvbjerg, 2017, 2014; Flyvbjerg et al., 2003), and they become increasingly relevant as their number grows globally (Flyvbjerg, 2016; Flyvbjerg et al., 2003; Woetzel et al., 2016). They include offshore wind farms (Brookes et al., 2017), hydro-power (Currie et al., 2021), transportation (Denicol et al., 2021), energy (Sovacool and Cooper, 2013) and can have a big impact on society and the environment (Biesenthal et al., 2018). Megaprojects could be seen as evidence of an acceleration phase in transitions that follow initial experimentation in diverse, small-scale niches, a phase where large-scale technology development and implementation is led by mission-driven innovation policies to sustainability challenges (Mazzucato, 2018, 2016).

This paper heeds the call for transitions research to engage with megaprojects (Sovacool and Geels, 2021). It engages with project management (PM), which is an expanding subfield of management and organization studies (Hornstein, 2015; Morris, 2012; Söderlund, 2011). Three observations substantiate the direction we take. First, core pillars of transitions frameworks and research i.e. actors, technologies and institutions, multi-level theorization and structuration theory (Geels, 2010), overlap with core pillars for research on change processes in project-based industries: multi-level theorization of change (Gann and Salter, 2000; Lundin et al., 2015; Sydow and Braun, 2018), and structuration theory (Floricel et al., 2014; Sydow and Windeler, 2020). For transitions and project management research, structuration provides the theoretical bedrock to analyse the duality of agency and structure (Farjoun, 2010). Second, PM represents an increasing share of organizational life (Davies and Brady, 2000; Hobday, 2000; Sydow et al., 2004; Turner, 1999) and organizational change processes (Lundin et al., 2015; Martinsuo and Hoverfält, 2018; Müller et al., 2016). Organizations with their structures and practices navigate the institutional landscape and engage in project-based organizing and learning (Sydow and Windeler, 2020). This is important as transitions are said to take place at the organizational field level (Geels and Schot, 2007). Third, organizational stability is a precondition for temporary organizing and project-driven change (Farjoun, 2010). Therefore, project success is best analysed in the context of a series of projects that organizations participate in, that are embedded in broader institutional processes (Dille and Söderlund, 2011; Engwall, 2003; Sense and Antoni, 2003), just as it is done with niches (Geels and Raven, 2006; Schot and Geels, 2008).

On the basis of these observations, this paper attempts a crossover between transitions, PM and megaprojects (Geels, 2011, 2010; Sovacool and Geels, 2021). It draws on the analysis of six megaprojects and the system wide-impact they have on digitalization of UK construction (Whyte, 2019; Davies et al., 2009). The megaproject scale raises tensions among actors as the risks they face are high and magnifies industry challenges of fragmentation, coordination, communication, project design and delivery, that need to be addressed (Egan, 1998; Latham, 1994; Levering et al., 2013). The solution to the challenges UK construction incumbents face comes from the adoption and adaptation of digital technologies from US defence and aerospace industry (Chasen, 1981; Llewelyn, 1989; Morris, 2013). Incumbents adopt and adapt technology to meet the broad scope, high-quality requirements of megaprojects, so they are lead users of digital technology (Bogers and Afuah A. Bastian, 2010; Von Hippel, 1986). The digitalization process is not marked by the entry of new firms or the decline of large incumbent firms but new entries of Information and Communication Technology (ICT) firms that supply design software packages.

Subsequent cumulative interactions between project actors and digital technology suppliers change the project-related and organizational practices they help constitute (Harty, 2005; Harty and Whyte, 2010; Morgan, 2019). The reorganization of practices within and between partners and suppliers drives the coevolution of organizations, competences and technological innovation (Ciarli et al., 2021; Leonard-Barton, 1988; Orlikowski, 1992). Some incumbents participate in subsequent megaprojects, so the co-adaptation of innovations and organizations extends to other industry actors and - along with the emergence of industry standards - transforms organizational structure and actor practices towards more integrated collaboration. This paper therefore addresses the following two Research Questions (RQ):

1. How digital technology outcomes aggregate and produce a system-wide transformational impact on the UK construction?
2. How digital technologies in megaprojects shape and are shaped by sociotechnical transitions?

The remainder of this paper is organised as follows. Section 2 introduces the theoretical background to the study and traces the correspondence of niches to projects. Section 3 summarizes data and methods used in our research. Section 4 presents the data of the case study of digital innovation in UK construction and its analysis to examine the study findings. Section 5 discusses the paper's findings with implications on the cross over between projects and transitions and Section 6 concludes the study.

2 Theoretical background

2.1 Sociotechnical transitions: Landscape, Regime and Niches

The Multiple-Level Perspective (MLP) is the predominant transitions framework where actors and institutions interact through different rules and induce transitions Geels (2004, 2017). Geels et al. (2016) distinguish among: (1) actors and social groups, (2) rules and institutions, and (3) technologies that interact dynamically. Actors and social groups use the rules of the institutions for example to introduce new technologies, make technology investments or develop new regulations and standards. These actors have different resources, such as money, knowledge, tools and opportunities to realize their decisions and influence social rules (Geels et al., 2016). Sociotechnical transitions research, then, focuses on system interconnections and social group dynamics that influence periods of system stability and change.

The sociotechnical regime is the central concept for the analysis of incumbent actors and activities that reproduce or change system elements. Actors form interdependent social groups, each with its own regime or set of rules. These rules align and coordinate the activities of actor groups that modulate system inertia and change (Geels et al., 2016; Geels and Schot, 2007). The sociotechnical regime, then, is the inter-regime rule set that aligns and coordinates intergroup activities that shape sociotechnical trajectories. The sociotechnical landscape is a wider canvas of macro influences that reinforce or stem niche and regime dynamics (Geels, 2011; Rip and Kemp, 1998).

Transitions are non-linear processes that result from the interactions of (a) niches, where innovations develop, (b) sociotechnical regimes of established practices and associated rules and (c) long term landscape trends (Geels, 2002; Rip and Kemp, 1998). Transitions have been conceptualised into four stylised pathways: 'substitution', 'transformation', 'reconfiguration', 'de-alignment and re-alignment' (Geels and Schot, 2007, Geels et al. 2016). It is possible that a transition will adhere to one, or shift from one pathway to another. Transitions are initiated when the sociotechnical regime is destabilised through niche innovations, internal regime tensions, landscape trends that put pressure on the focal regime (e.g. climate, economic, cultural, demographic and other), and external influences from other systems, regimes or niches (Geels and Schot, 2007; Papachristos et al., 2013; Raven, 2007; Rosenbloom, 2020). A transition is not likely to result from a single successful experiment, rather it proceeds through a process of accumulation of local niche activities where innovations are used in several application domains and subsequently enter increasingly larger (market) niches (Geels, 2002; Geels and Schot, 2007).

2.2 Niche development and empowerment

Niches can act as peripheral, 'protective spaces' where selection criteria are more favourable to new technologies than in the mainstream markets that operate under the dominant regime (Levinthal, 1998; Schot and Geels, 2007). In these shielded markets, the interaction of users with producers, gives rise to mutual learning and expectation articulation processes (Hoogma et al., 2002; Kemp et al., 1998). Niche *nurturing* involves articulation of actor *expectations* and visions, development of social *networks*, and *learning* processes (Schot and Geels, 2008). Learning processes contribute to niche development and involve first and second order processes. In the early stages of niche development, technology performance criteria are unclear, so technological competition is based on future expectations rather than current performance (Budde and Konrad, 2019; Klepper, 1997; Rosenberg, 1994).

Expectations and visions motivate, engage and align actors to commit their resources towards promising technological fields (Konrad, 2006), and guide niche learning and development (Geels and Raven, 2006). Niche *empowerment* is integral to transitions because it can influence the regime. Two empowerment processes modulate the interface between niche(s) and the regime (Raven, 2007; Smith et al., 2010; Smith and Raven, 2012): *fit and conform* and *stretch and transform*. Niches are empowered through *stretch and transformation*, by presenting a realistic alternative to problems, instabilities and tensions the regime experiences, such that tech implementation and institutionalization of niche practices becomes accepted by regime actors. In *fit and conform*, niches are empowered when they improve along established performance dimensions.

The process of technology implementation involves the mutual adaptation of technology and organizations (Leonard-Barton, 1988; Orlikowski, 1992). Market niches materialize as the product of organizational action (Astley, 1985; McKelvey, 1982). Thus, markets, user preferences and competences may need to be co-constructed with new technologies (Oudshoorn and Pinch, 2003), to meet various attributes and selection criteria, such as price/performance, and the minimum functionality threshold for a technology in an application domain (Adner and Levinthal, 2001). Technology may have a more aggregate effect at the organizational field level, if technological functionality increases, or its cost is reduced and subsequently reaches larger, mainstream niches and becomes a general-purpose technology (Rosenberg, 1976).

2.3 Niche aggregation and structuration from local to the global level

The process of niche aggregation involves four phases (Geels and Deuten, 2006). In the first (local) phase, new technologies emerge or are introduced through technology absorption and relatively independent new entrants in local practices who create local knowledge for their own purposes. Actor networks form around specific projects, locally applicable knowledge and practices, that provide the context where novelty and new technical knowledge may emerge endogenously in response to local problems and speciation.

In the second (inter-local) phase, technological knowledge flows initiate in actor networks. Learning and accumulation of experiences has an inter-organizational but still local niche character through people, professional societies and industry associations that stimulate and facilitate the production and circulation of technical knowledge. Technology suppliers increasingly interact with other producers, suppliers, users and regulators. When innovation experience is transferred from one project to another then general lessons are developed, and local knowledge is gradually absorbed into generic knowledge (Fleck, 1994). Thus, cognitive rules are initially fuzzy and unclear but eventually they become specific, codified, shared and stable over time (Schot and Geels, 2008). This second phase ends when demands and criteria on technology performance increase or change.

In the third (trans-local) phase, knowledge production and circulation increase and acquire a global scope as groups of firms coalesce around their collective interests. In this phase a knowledge infrastructure emerges with dedicated journals and conferences for knowledge circulation, and with intermediary actors that perform dedicated knowledge activities at the global level to create, standardise, and distribute knowledge (Kivimaa et al., 2018; Schmidt and Werle, 1998). Aggregation from the local to the global level involves the transformation of diverse local and context-specific knowledge and selection criteria through codification, and formulation of best practices into robust, general and abstract knowledge and cognitive rules that are no longer tied to a specific context (Geels and Deuten, 2006; Raven and Geels, 2010).

In the fourth (global/cosmopolitan) phase, dominant cognitive rules and a global stock of knowledge, technology artefacts and standards become established and shape local-level activities. Technological development thus proceeds simultaneously at local and global levels (Geels and Deuten, 2006; Geels and Raven, 2006; Schot and Geels, 2008). Therefore, the aggregation of peripheral niches produces generalizable knowledge through shared cognitive rules, structures and standards, and a system wide impact that catalyses a transition (Geels and Deuten, 2006; Geels and Raven, 2006; Raven and Geels, 2010; Schot and Geels, 2008). Standards are the most tangible and by definition codified outcomes of the aggregation process (Geels and Deuten, 2006; Geels and Raven, 2006). Standards bind a sociotechnical system together and contribute to its momentum, inertia and trajectory (Bakker et al., 2015).

2.4 Megaprojects as sociotechnical niches

A motivation to view megaprojects as sociotechnical niches is the argument made in PM literature that projects must be considered as sociotechnical endeavours embedded in complex institutional settings (Biesenthal et al., 2018). Modern infrastructures in transport, energy, and telecommunications are delivered through megaprojects, with investment exceeding $1 billion. Megaprojects are capital intensive, large-scale, complex enterprises where diverse actors collaborate to deliver an intended outcome (Flyvbjerg, 2014). In this respect, megaprojects offer a rich setting for transitions research to study the interplay of institutions, actors and technology due to their longevity, pervasiveness and embeddedness (Blomquist and Packendorff, 1998; Brookes et al., 2017). Their institutional complexity is seen in their front-end management, the promoter's role (Gil and Pinto, 2018), their embeddedness (Blomquist and Packendorff, 1998) and involvement of numerous external stakeholders, such as market and government policy, which are also core regime elements.

Moreover, megaprojects exhibit a range of processes and attributes that we argue are conducive to their conceptualisation as niches for transitions research. Megaproject duration and delivery phases span across years or even decades, and may give rise to interorganizational relations and learning processes similar to those of permanent organizations that participate in niches and thus transition research could draw on PM research on learning. Projects are milieus for knowledge creation due to their transience and interdisciplinary nature (Gann and Salter, 2000; Grabher, 2004; Hobday, 2000). Essential learning processes arise at the interface between a project and the organizations, networks, and institutions in which it is embedded (Prencipe and Tell, 2001. Inter-project learning depends on organizational structures between projects, interproject assimilation practices, and actor alignment that facilitates the relationship with other projects (Lundin et al., 2015; Sense and Antoni, 2003). Aggregation dynamics may develop through organizational adoption and adaptation to technology, and the ways partners relate to projects (Manning and Sydow, 2011). The variety of collaborative paths and projects that may develop over time (Brady and Davies, 2004), may contribute to a variety of scale up, aggregation trajectories, and industry wide impact.

The implication is that no project unfolds in an organizational field vacuum, so it needs to be conceptualized as a history-dependent and institutionally-embedded unit of analysis to explain project success or failure better (Biesenthal et al., 2018; Engwall, 2003). To this end, the study analyses how digital technology implementation in megaprojects aggregates and transforms UK construction.

3 Methodology

We investigate the relation between megaprojects and system level digitalization in UK construction with a case study approach (George and Bennett, 2004; Yin, 1984), as it is appropriate for the analysis of context rich phenomena (Eisenhardt, 1989). A single embedded case study design is used here (Yin 1984) to analyse six intertwined infrastructure projects in UK (Engwall, 2003). The six embedded cases presented were selected through theoretical sampling (Eisenhardt and Graebner, 2007; Pettigrew, 1990) as they are particularly instrumental in industry transformation through digitalization. In chronological order, the six projects are: (i) the Channel Tunnel Rail Link, (ii) Heathrow Terminal 5, (iii) London Olympics, (iv) Crossrail, (v) Thames Tideway and (vi) High Speed Two. Projects i-iv are completed, and projects v-vi are ongoing (more information is in Appendix B). These projects have not been treated yet as part of a single longitudinal study on industry transformation, while they have been the subject of PM related research (Brady and Davies, 2014; Davies et al., 2009; Davies and Mackenzie, 2014; Dodgson et al., 2015; Gaunt, 2017; Genus, 1997; Zerjav et al., 2021).

The cases offer opportunities for complementary and synergistic data gathering and analysis. The cases of completed projects offer the opportunity to study technology aggregation retrospectively in the context of the overall transition pattern while the study of ongoing cases provides a close-up view on project evolution over and the mutual adaptation of technology and organizations (Leonard-Barton, 1990, 1988). Case data span 36 years from 1985 to 2021, collected through academic literature, government and industry reports, as well as interviews with eight industry experts, policy makers and practitioners which contribute to the external validity of the research (Sarantakos, 2005). Interviewees have diverse backgrounds and roles (see interviewee profiles in Appendix A): some have direct involvement in past and ongoing infrastructure projects: three interviewees (Int 1, 4 and 8) have significant industry and policy experience, and two hold key management roles in ongoing infrastructure projects (Int 7 and Int 2).

The cases are explored through a process lens (Langley, 1999; Langley et al., 2013). We first describe the institutional setting for the embedded cases. Then, the managerial choices made and emergent processes in each project are described following guidelines for qualitative inquiry (Denzin and Lincoln, 2017). The longitudinal view on the cases reveals the inter-organizational processes at work and the bidirectional influence of project organization and industry level developments. We use a combination of narrative and visual mapping as the strengths of each method counter the weaknesses of the other (Jick, 1979; Johnson et al., 2017). Diagrams do not constitute theory development on their own, but are part of theory building blocks (Sutton and Staw, 1995), and theorization (Langley and Ravasi, 2019; Weick, 1995) .

4 Findings

4.1 Case institutional setting

The 2011 Government Construction Strategy (GCS) focused on the need for widespread adoption of digital technologies such as Building Information Modeling (BIM) (Cabinet Office, 2011). Through this milestone development, the Government mandated that BIM Level 2 should be used on all public sector projects starting after April 2016 (GCCG, 2011). The mandate called for all project and asset information, documentation and data to be digital and specified the collaborative use of BIM models and digital objects (Papadonikolaki et al. 2019). To support these efforts, the UK government created the UK BIM Task Group which was publicly-funded until 2017. Thereafter a period of intensive standardization followed, with high levels of information exchange, deliberations, and strong leadership. In particular, the British Standards Institute (BSI) issued a suite of Publicly Available Specifications (PAS) number 1192 with parts 2-6 published between 2013 and 2015.

In 2013, the Government issued the Construction 2025: Industry Strategy to reaffirm its strong support for BIM. It emphasised the joint commitment and close collaboration of government and industry to the BIM vision and programme. The strategy outlined a vision that all government procured projects would be delivered through a digitally-enabled delivery and lead eventually to a wider offsite manufacturing strategy. In 2016, the Cabinet Office and the Infrastructure and Projects Authority (IPA) issued the 2016-2020 GSC which built upon the 2011 strategy, emphasising BIM and Digital Construction as *"an important part of the strategy and is helping to increase productivity and collaboration through technology"* (Office, 2016). Presently, BIM is considered the most representative digital technology and information aggregator in construction globally. The Farmer Review (2016) commissioned by the Construction Leadership Council at the request of the UK Government resonated with earlier reports by Wolstenholme et al. (2009), Egan (1998) and Latham (1994) attributing productivity losses and lack of collaboration in construction to a paucity of innovation and widespread skills shortage. The review called for action in light of the announced Thames Tideway and High Speed 2 projects in London.

4.2 Channel Tunnel (CT) (1985–1994)

UK construction in the mid- '80s was characterised by inefficiency and low digitisation. The discourse on improvements in UK construction included visions of partnering, supply chain management, and lean manufacturing philosophy, all of which were imported from other sectors, such as manufacturing (Pavitt, 1984; Reichstein et al., 2005). In this context, CT was seen as a key infrastructure project for change in UK construction sector. A consortium of Bechtel, Arup, Systra, and Halcrow was established to run the $10.3billion Channel Tunnel Rail Link project linking UK to Europe's high-speed rail network (Davies et al., 2009). The technical complexity of CT pushed the boundaries of technology innovation in UK construction.

At the time, the method to produce and share design information was through 2D plans (Harty and Whyte, 2010). Digital innovations introduced from the US were a radical departure from prior established ways of working (Genus, 1997). They enabled the exchange of building information through Computer-Aided Design (CAD) applications, the creation of a virtual building through software before commencement of on-site work (Harty, 2005), and limited error-prone human interventions (Eastman, 1999). As Int-6 explained, 3D modelling tools (Pöttler, 1992) and other computer-based tools to deal with interoperability issues among different systems were tested in CT for project planning, cost management, procurement systems, and for facility management after construction.

The implementation of 3D CAD in drafting departments required broader organizational adaptations and support, as its repercussions reverberated throughout the inter-organizational network of project actors. Instead of 2D plans to be used and adjusted on-site, 3D CAD required full design specification upfront, which left no room for design alterations during construction. Innovations used in CT paved the way for two subsequent CT phases in 2003 and 2007 (Arup, 2004; Pollalis and Georgoulias, 2008). The CT project informed the Latham (1994) and Egan (1998) reports that called for increased supply chain integration and collaboration and digital technology use to improve industry performance (Papadonikolaki and Wamelink, 2017).

4.3 Heathrow Terminal 5 (T5) (1999–2008)

T5 was a $8.5 billion project for a new terminal at Heathrow airport to increase its annual capacity from 67 million to 95 million passengers. Due to its size, the T5 project became a program of industry-wide change in the UK (Davies et al., 2009). British Airports Authority (BAA) committed to 3D CAD implementation for coordination of design and construction, and information management across the whole project (Harty, 2005). BAA in consultation with partners pursued an integrated team approach to technology introduction and use in T5, that substituted some traditional drafting practices. This was shaped by T5 project managers who drew on the previous Heathrow T4 project (Harty, 2005). Personnel transfer from CT to T5 facilitated the further "evolution of digital technologies there" (Int-6). This approach was enabled by inter-compatible design and drafting software packages, mediated by a document management database.

The use of BIM in T5 aimed to create a single-model environment to improve coordination in the construction process, systems integration and information flows across actors, so that problems could be identified prior to work on-site where errors are costly (Davies et al., 2009). In T5, BIM can be described as a systemic innovation, as its consequences spread across multiple partner tiers (Harty, 2005). BIM is not a singular, stand-alone technology like CAD, but a more platform-like and thus disruptive innovation at the organizational level (Morgan, 2019). It is the result of evolving efforts by industry consortia, such as BuildingSMART to standardize building information (East and Smith, 2016).

The benefits of BIM were enough to convince project engineers and drafters they had to change their practices but were not enough to drive technology implementation at the organizational level. Considerable work was necessary to organise a coherent and inclusive system of technologies and practices in alignment to the diverse expectations and visions of the project (Harty, 2005). Negotiations between project actors indicated the software packages as necessary to align the BAA vision and the visions of services engineers and drafters. However, existing software packages could not facilitate the BAA vision and meet the selection criteria of project actors. This required that software had to transform from being primarily a design tool for 3D design to a manufacturing and control tool as well. Such digital innovations were highly influential in allowing the design to be engineered: for instance, model buckling analysis and sophisticated wind analysis were made possible on the complex roof structure of the terminal (Arup, 2006).

T5 project activities thus shaped software package functionality and triggered a cycle of mutual technology and adaptation (Leonard-Barton, 1988; Morgan, 2019; Tyre and Orlikowski, 1994). Technologies were incorporated into practices that already utilized a diverse network of material and digital artifacts. Moving towards a digitally oriented process was not just a simple case of technology substitution but fundamentally changing the practices they constituted (Harty, 2005; Harty and Whyte, 2010). However, configurations of practices already in place in T5 proved robust so the more initiatives to change challenged established practices and ways of work, the more they were resisted (Harty and Whyte, 2010). Eventually, the digital link between design and fabrication had to be dropped due to such difficulties.

4.4 London Olympics 2012 (2005–2012)

London Olympics transformed Stratford in east London, into a 2.5 km^2 Olympic Park with an athletics stadium, aquatics centre and velodrome. The London Olympics project (LO) drew on the lessons of T5 with digital technologies and software tools used for coordination at each phase of system integration project design and documentation management, e.g. in ProjectWise (Davies et al., 2009; Davies and Mackenzie, 2014). At the same time, systems integration related to collaborative teamwork and managing uncertainty by mutual adjustment and collection of new information. Legacy issues were widely considered in LO, described as a ‘field-configuring event’ (Thiel and Grabher, 2015). Several senior managers from London Olympics transferred their experience and innovative ideas on digital innovation to Crossrail, including Andrew Wolstenholme chief executive at Crossrail and former programme director at T5 (Wolstenholme et al., 2009).

At the same time, the UK government took steps to promote digitalization of UK construction through institutional projects (Holm, 1995). This included Avanti, which was a project to enable effective team collaboration through technology (Morgan, 2017). It was an inter-institutional collaboration among the Department of Trade and Industry supported by large UK construction firms, universities and R&D organizations, and BuildingSMART (formerly International Alliance for Interoperability). Funded by the UK government, Avanti drew several major industry partners together to create a culture, processes and digital tools to enable team collaboration (Morgan, 2019) through the use of two-dimensional (2D) digital design.

Avanti became the basis of the BIM British Standard BS1192. Such was the industry enthusiasm for Avanti, that it continued to be supported after government funding had run out. The Avanti principles were subsequently used in the Victoria Station Upgrade project to manage information flows and partner collaboration and "*get people to trust that data*" (Int-3). The significance of Avanti lay not only in its influence in establishing data standards but also in addressing cultural change: *"in an industry where adversarial practices ruled…we paid a lot of attention to establishing a collaborative culture in Avanti, with hindsight this was as great an achievement of the project as some of the more technical advances".* (Int-8).

4.5 Crossrail (2008–2022)

Crossrail is the biggest civil engineering project in Europe and the basis for several digital innovations in the AEC industry (Arup, 2012). Crossrail will provide high-frequency suburban passenger service crossing London from west to east. Crossrail started with 2D deliverables before the 2011 UK BIM mandate, but was completed using BIM and 3D digital deliverables. It was among the first UK projects to become PAS1192-compliant and use BIM as a digital platform for other innovations, such as laser scanning and augmented reality. However, the BIM Level 2 criteria were seen as obscure and too *"open to interpretation, to be legally enforceable, but we were all aiming towards that 2016 deadline"* resulting in standards not *"as clear and concise as we would want"* (Int-3), which created challenges in the project and technology uptake. The innovation strategy followed at Crossrail received considerable scholarly and practitioner attention (Debarro et al., 2015). The Innovate 18 programme, was set up in association with Imperial College as a formal element of Crossrail delivery aiming to create a collaborative innovation culture across the project, partners and suppliers (Debarro et al., 2015; Pelton et al., 2017).

The leadership shown by the government was catalytic to reconfigure work with digital innovations and *"really changed where we were."* (Int-3). From the perspective of the private sector, the government both local and national did some brilliant work to modernise planning policy and drive "*digital transformation in large-*

scale infrastructure through the BIM policy" (Int-5). To further digital innovation in the industry, a BIM Academy was established in partnership with Bentley software to support the Government Construction Strategy, increase the use of BIM and create a lasting legacy of best practices in the industry (Munsi, 2012). The Academy training helps industry constructors to transfer their knowledge to other major projects such as HS2 and TT. Both LO and Crossrail had a strong emphasis on passing on lessons learnt to later infrastructure projects. This is particularly evident in HS2 and Thames Tideway (Pelton et al., 2017). Many senior managers from the London Olympics and Crossrail went on to work at TT or HS2, thereby transferring knowledge on digital technologies between these megaprojects.

4.6 Thames Tideway (TT) (2012–2023)

The TT project is a tunnel running mostly under the tidal section of the River Thames through central London to capture, store and convey almost all the raw sewage and rainwater that currently overflows into the river. The TT is the first megaproject to adhere to BIM Level 2 standards. It is a landmark development in digital modelling, requiring that all project actors use digital model-based delivery (Gaunt, 2017). Significant efforts were made during initial procurement to assess the risks implicit in BIM delivery. However, while contractors were required to use BIM delivery, the TT team chose to adopt a 'technology agnostic' approach during tendering. The reason was prior experience from projects including Crossrail "*where they had imposed a particular bespoke software or the client hosted everything'* meaning that *'the risk was with the client.*" (Int-7). The TT team defined project deliverables from a digital blueprint and the BIM Execution Plan but encouraged contractors to use tools they already had expertise in so that they would "*be able to go back to their own home organisations and utilise the latest, greatest software, where possible.*" (Int-7).

The TT team is also heavily involved in the Infrastructure Client Group to promote digitalization in construction and align *"to the wider UK rollout, especially infrastructure" (Int-7).* The aim is to draw on the lessons of the Crossrail and Olympics projects, create a digital learning legacy for construction, pass on lessons to HS2 and share best practices. 2016 marked a turning point with less government involvement but industry sentiment was that government support was still necessary "*to try and drive that leadership from the top"* (Int-3). Initially, there were great expectations that the industry would follow through with best practices in BIM Level 2 and the insurance sector would play a key part, but it became apparent that time was necessary "*to see that properly emerge. I believe that's starting to happen, however."* (Int-1).

4.7 High Speed Two (HS2) (Phase 1: authorised in 2017 2029-2033)

The first phase of HS2 is a major high-speed rail line that links London and Birmingham. Building upon developments from previous projects, but also benefitting by movement of experienced staff from LO and Crossrail, HS2 will collect and utilise knowledge to construct the digital twin of the asset, that mirrors the physical infrastructure and enables scenario simulations. This is one of several industry initiatives in Digital Built Britain, that *"can certainly go a long way, and that would probably be HS2's digital legacy."* (Int-2). In this regard the HS2 team works closely with government departments, with major infrastructure programmes, and professional institutions to try and *"be proactive in developing standards and making sure that our requirements, our expectations from our supply chain, are reasonable."* (Int-2).

The HS2 project has redefined digital innovation in UK construction by "*looking at developing competencies which are not just limited to BIM in a sense that it's been defined as just a modelling or a CAD tool*." (Int-2). There is a growing awareness of the digital legacy the project creates, and it becomes clear that it is necessary to "*look at this as a wider data management piece*" (Int-2). In this respect, standards like ISO19650 are a good starting point because they look at "*at information management in its wider sense and its wider context*" (Int-2). They are also pioneering solutions that benefit the entire industry and aim to create lasting change such as the HS2 BIM upskilling platform (HS2, 2019).

Although regulation activities stopped with the 2016 mandate, organizations since have increasingly committed to digital practices. The perception in the industry changed from "*Digital is something interesting. It's something on the side,"* to *"It's core to our business … It's not a case of digital is a nice thing you do in your spare time."* (Int-5). This indicates the increased legitimacy of digital competences and practices. Despite the marked change, the five years from 2011 to 2016 *"was an incredibly short amount of time to change an industry which, […] I think that hasn't entirely happened yet. I think we still need a lot more leadership. We need a lot more guidance."* (Int-3). Indicative of the progress made is the refinement of ISO19650 which still is *"not as enforceable in the client world as I think it should be."* (Int-3).

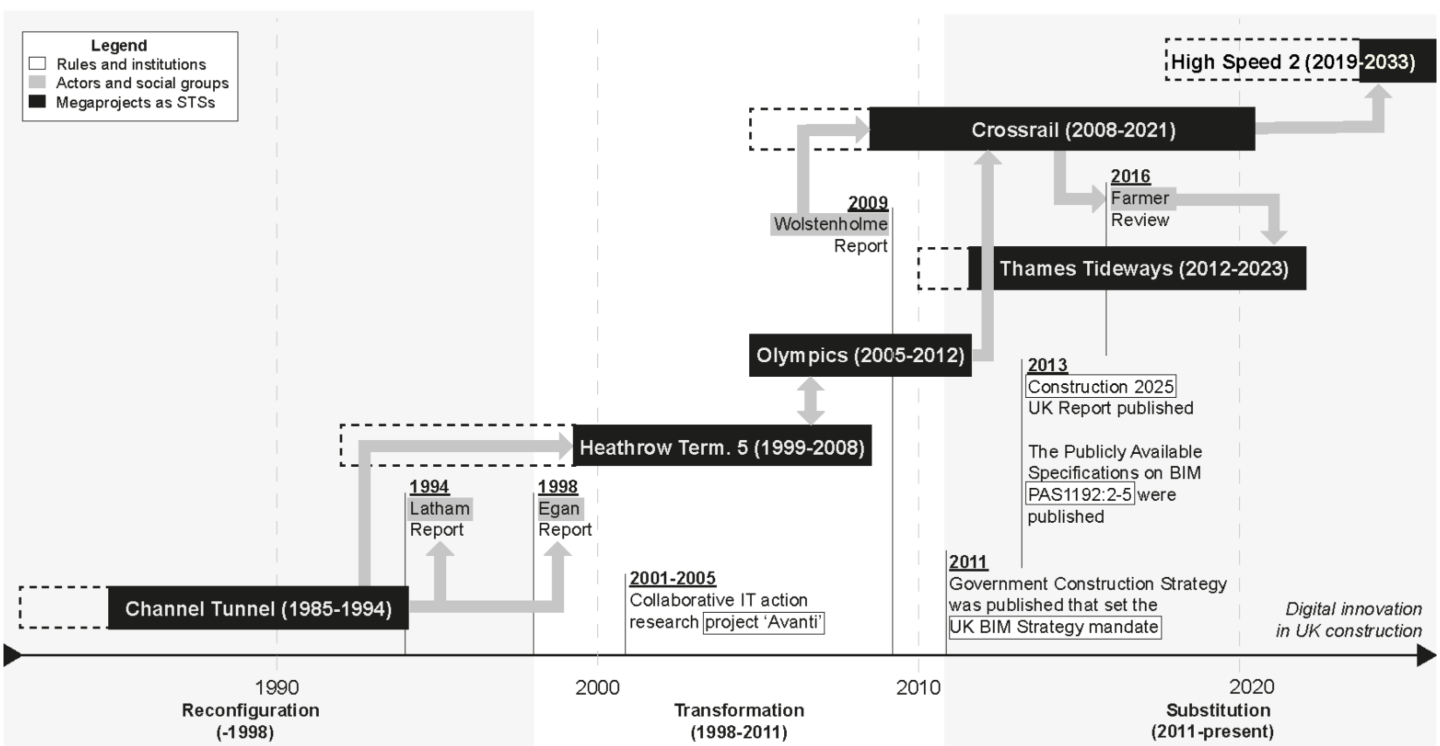
Despite the UK government leadership, the *"local government doesn't seem to actually drive the mandate, that it was pushed through for* 2016*. So, we can already see setbacks. We want it to work, but we have really setbacks that we need to overcome"* (Int-4). Industry digitalization requires collective action "*So, those early adopters in terms of procurement and use of BIM used - to the majority, again, to stage open book tender. So, technology could actually assist but, again, it needs the combination of that collaborative work that we need to bring together*." (Int-4). For example, in some of the pilot projects in the Ministry of Justice "*they actually brought in the supply chain, and even the operators, and they were involved in the dialogue very early on in the design stage to be able to really*." (Int-4). Further evidence of industry change can be found in 'Project 13', a recent industry-led collaborative endeavour that seeks to develop a new business model, based on an enterprise, not on traditional transactional arrangements, to improve UK construction. Among the ambitions of the Infrastructure Client Group (ICG) is to *"establish standards that all ICG members will sign up to and enforce across all of their projects".*

5 Discussion

5.1 Aggregation of digital technologies

To address the first question, which focuses on system-wide transformational impacts in UK construction, the analysis indicates that the evolution of digital technologies and related standards in UK construction has gone through several stages, punctuated by regulation, and marked by the move of scholars and practitioners towards broader scope for BIM (Dainty et al., 2017; Morgan, 2019). Drawing on the preceding sections, Figure 1 summarises the process of aggregation of digital transition in UK construction and juxtaposes (i) rules and institutions, (ii) actors and social groups and (iii) digital technologies with the temporal sequence of megaprojects, and policy reports. By viewing infrastructure projects as STS niches, a key contribution of this study is apparent. Our analysis suggests that an alternative transformation process drives change from the regime core to its periphery. This is interesting but in addition one could argue that this transition does not adhere closely to one of the proposed stylised pathways (Geels and Schot, 2007). Rather, we distinguish three phases (Figure 1) in this process for which a tentative case can be made as to its correspondence to a pathway.

Figure 1: Timeline of digital technologies in UK construction influencing and being influenced by institutions, actors and megaprojects as sociotechnical systems (dashed lines indicate authorisation dates).



In the first phase, digital technologies are adopted to enhance design and communication processes in construction supply chains so that the production and delivery onsite of complete blueprints is done with minimum errors. The incremental adoption of technologies in existing design and construction incumbent practices resembles the *reconfiguration* pathway where innovations are adopted in a symbiotic way in a regime to solve local problems, in our case the challenges that actors in individual megaprojects face. This innovation adoption process triggers subsequently further adjustments in the basic architecture of the regime. The second phase has elements of *transformation* pathway, as innovations are still being developed and refined and at the same time regime actors modify the development direction of their capabilities to align them to the new standards they have to adhere to. This was in part because technologies where not endemic to the construction industry. Section 4 documents how industry incumbents engaged with software vendors in the development of digital technologies, and with government initiatives in the development of relevant industry standards. The third phase has elements of *substitution* pathway in that BIM solutions are available to industry actors and are developed sufficiently and specifically to their needs. To the extent that actors commit the necessary resources, BIM can potentially substitute completely previous practices and processes industry actors have in place in their construction supply chains. Table 1 shows the sociotechnical transitions in digital technologies through UK megaprojects.

Table 1: Transition pathways of digital technologies through UK megaprojects along three categories (institutions, actors and technologies), based on framework by Geels et al. (2016).

Transition pathways	**Rules and institutions**	**Actors and social groups**	**Digital technologies and STS**
Reconfiguration (-1998)	Limited institutional change from government-sponsored industry reports calling for change No rules developed	Firms become sporadically aware of the need for change No new entrants	In complex infrastructure projects, the need for technological change is accentuated Digital tools complement and substitute existing
Transformation (1998-2011)	Institutional change by sponsoring an institutional and collaborative project to inspire change Project outputs become basis of British Standards	Incumbents reorient incrementally by adjusting their processes New government-sponsored groups and communities to drive change emerge	Incremental progress in existing technologies Incorporation of symbiotic niche-innovations and add-ons that change the processes
Substitution (2011-present)	Substantial institutional involvement via mandates for new technology in public procurement Issuing of suites of standards to lead change	Incumbent firms reorient substantially, to new technology and business model New alliances between incumbents and new entrants	From initial add-ons to new hybrids of new and existing technologies Partial or full technical substitution of tools that brings new processes

5.2 *Megaprojects in sociotechnical transitions processes*

To address the second question on how technologies in megaprojects drive sociotechnical transitions and vice versa, we start from framing infrastructure megaprojects as niches where incumbent actors engage in joint endeavours, standardization, and cooperation with the government. The scale of megaprojects magnifies coordination and performance problems due to industry fragmentation and intensifies partner tensions. Technology adoption triggers the digitalization process and the six megaprojects drive the aggregation process. They provide the impetus for digital technology implementation, a test bed for the refinement of its selection criteria, and the development of new regulations and standards.

Sociotechnical changes at the firm and regime levels influence mutually constitutive relations between institutions, organizations, projects and actors (Morgan, 2019; Shibeika and Harty, 2015). The flow of key personnel across projects and institutions and their boundary-spanning capabilities drives and is driven by digital innovation and standardization (Koskinen, 2008; Levina and Vaast, 2005). Standardization is punctuated by two milestones, the Egan Report (1998) and the 2011 mandate for digital project delivery. Particularly after 2011, the Crossrail, TT and HS2 consortia formed strategic alliances with the UK government to drive digital innovation and standardization which were essential for digital technology evolution.

To understand how the digitalization process begun at the regime core and rippled out to the periphery of the construction industry, one has to understand that large incumbent firms in UK construction were in a position to impose their project related requirements to their 1st and 2nd tier suppliers. These requirements emanated from government strategic procurement policies, institutional developments and standards, for example, the Avanti project (2001-2005) set the foundation for PAS1192 standards issued during 2013-2015. The regime core to periphery dynamics then unfold over time because BIM adoption and implementation at the project level require collaboration between partner firms (Harty, 2005) and trigger organizational changes (Morgan, 2019; Peansupap and Walker, 2007). The establishment of local standards of practice and organizational changes that initially span design to actual construction and post commission work, eventually aggregate to institutional changes that ripple across the industry (Boland et al., 2007). They have system wide impact as they change established organizational practices and technology selection criteria, and stimulate the development and use of sector specific software packages that are considered the norm today.

5.3 Theoretical implications

The case offers a clear example of how incumbents in capital-intensive industries survive the challenge an innovation may present (Bergek et al., 2013; Berggren et al., 2015; Cohen and Tripsas, 2018). This would suggest that incumbent chances of survival during a transition are better than what is implied in most transition research. Indeed, industrial organization research indicates industry incumbents have better survival chances than entrants of an industry in its mature phase (Agarwal et al., 2002; Agarwal and Gort, 1996; Christensen et al., 1998; Klepper, 1997; Malerba and Orsenigo, 1996; Suarez and Utterback, 1995). The importance of this is significant in terms of transitions research as large incumbent organizations often have a large societal impact (Matten and Crane, 2005), which can manifest both in terms of stalling or accelerating a transition.

The case of megaprojects deviates in a number of ways from a narrative where new entrants and outsiders challenge dominant incumbent actors and regimes. Megaprojects provide fertile ground for transitions research that may uncover a greater variety in aggregation patterns and transition pathways. Firs, the positive role of incumbents in catalysing rather than raising barriers to change indicates that scholars should analyse symmetrically niche-to-regime activities and regime-to-niche activities. This may include the strategic reorientation of incumbent actors in the focal regime or capital-intensive industries.

Second, the technology use in megaprojects is in stark contrast to the system innovation pattern that begins with diffuse niche visions, open-ended experimentation, expectations and diverse search and technology development processes and develop to present a credible alternative to the dominant regime (Kemp et al., 1998; Schot and Geels, 2008; Smith and Raven, 2012; Turnheim and Geels, 2019). This may be a feature pertinent to infrastructure projects that need prior consensus and agreement to start, where failure is simply not an option, in part because of their high profile. Moreover, the digitalization process seems to broaden rather than become more specific, as suggested in the literature (Schot and Geels, 2008). Digital technologies become linked to multiple possibilities e.g. advanced applications of BIM, additive manufacturing, artificial intelligence and robotics, the internet of things, big data analytics and Blockchain technology.

Finally, bi-directional exchange between PM research and transition research offers some promising avenues through structuration theory (Floricel et al., 2014), and multi-level theorization that includes the firm level and the institutional - organizational field level (Gann and Salter, 2000; Lundin et al., 2015; Sydow and Braun, 2018), to examine temporalities and temporary/permanent organizing interaction at macro-meso-micro levels, the relation of projects to institutions (Biesenthal et al., 2018), and project governance (Müller et al., 2016). With macro scale initiatives for macro scale changes as a starting point, researchers in transitions research and PM could look for other similar theoretical tensions and use them to stimulate better theorizing (Swedberg, 2017; Weick, 1995), and the development of more encompassing theories (Poole and van de Ven, 1989).

5.4 Implications for research and practice

Our cases show the role of strong guidance, consensus, early direction-setting, and sustained resource commitments, e.g. national R&D funding, national strategic procurement for transition processes. The industry reports exemplify the strategic consensus and the vision for the industry (Egan, 1998; Farmer, 2016; Latham, 1994; Wolstenholme et al., 2009). They provide a strong impetus for change supported by government level standardisation initiatives such as the Avanti project, that is catalysed by the six megaprojects. These projects serve as milestones because of the significance of the technology verification and exemplification they enable, but also because their design implications were systematically replicated in later projects, supporting step-changes in the overall system trajectory. The projects influenced the speed of technology diffusion and organizational change and its directionality.

The purposeful character and focus of industry change efforts indicates that each megaproject can be considered as a niche for analysis purposes (Turnheim and Geels, 2019). Megaprojects with the extensive range of organisations and institutions involved, can function as institutional change levers or even political projects by invoking the collective action of political actors (Holm, 1995). For example, megaproject executives were aware of and keen to leave a 'digital legacy' (Munsi, 2012). It would seem that the proposition that single projects are not so important for niche development does not apply in our case (Hoogma et al., 2002).

While the sheer scale of megaprojects may seemingly provide little scope to consider agency, managerial cognition in fact plays a key role in identifying capabilities suitable for the environment where an organization operates (Lavie, 2006). The case of Wolstenholme is illustrative in this respect. Managerial cognition enables organizations to reconfigure their capabilities through substitution, evolution or transformation (Cohen and Tripsas, 2018; Lavie, 2006). A manager's interpretations of the external landscape will affect how they see their own organization's abilities to respond to it (Milliken, 1987). The cases highlight that the match between organizational capabilities and a market opportunity is not sufficient for change if managerial beliefs e.g. of Wolstenholme, are not aligned with the opportunity (Eggers and Kaplan, 2013, 2009; Tripsas and Gavetti, 2000).

Our findings also have relevance for current debates on mission-oriented innovation policy (Mazzucato, 2018, 2016; Schot and Steinmueller, 2018) and policy mixes in sustainability transitions (Kanger et al., 2020; Kivimaa and Kern, 2016). While bottom-up experimentation remains relevant, our findings demonstrate that specific visions, political commitments and guided search paths can effectively stimulate industry transformation, especially when supported by stable funding streams and involving long-term strategic partnerships with resourceful actors that have relevant skills and capabilities. Policymakers can also use landmark projects to stimulate emerging innovation trajectories but should simultaneously build dedicated knowledge infrastructures to enable knowledge circulation between implementation sites and guide the standardisation of system designs.

6 Conclusions

The framing of digital technology adoption in UK megaprojects as a sociotechnical transition process that involves several megaprojects, offers an interesting alternative to the dominant transition's narrative where sociotechnical processes at the periphery of a dominant regime, accumulate momentum, scale up and eventually transform it. In contrast to this dominant narrative, the case analysed in this paper indicates that infrastructure systems may exhibit the reverse process. The analysis of UK megaprojects shows how digital technologies introduced in construction, shape and are shaped by the interplay of institutional and organisational change processes of incumbents at the regime core. They are shown to enable and drive, rather than inhibit the aggregation trajectory of project based digital innovation. It is underlined by actors whose mobility across megaprojects and institutions is instrumental in the development of digital technology standards and regulation.

The sociotechnical perspective and analysis of projects as part of broader system level changes may be of interest to project management scholars that view projects primarily as distinct units of analysis. The implication of this study is to highlight potential conceptual cross overs between PM and transition research. Understanding the inter-relationships among key infrastructure projects, institutions, actors and how they influence digital innovation is a timely subject for both project management and transition research. It will help prepare for and identify patterns and opportunities to manage the unprecedented pace of emergent digital technologies that influence the industry. Apart from construction, these findings are valuable for other sectors, because the built environment allows us to study this relatively slow transformation over three decades and identify mechanisms and inter-relations that are hardly noticeable in other sectors, where the pace of innovation is more accelerated. In this respect the case may be shed light on contemporaneous projectification processes in other systems.

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Appendix A

Table 1: Profiles and identifiers of the interviewees for external validation of the research.

Identifier	Current role	Professional Background	Area of expertise / relation to infrastructure	Institutional roles held currently or in the past
Int-1	Chief Scientist at the Building Research Establishment (BRE) and Professor at Higher Education	Chartered Engineer and a Fellow of the Royal Academy of Engineering;	Significant policy and industry expertise	Chief Scientific Advisor for the Department of Communities & Local Government. Chair of BuildingSMART UK, Past President of the Institute of Engineering and technology
Int-2	BIM Strategy Manager at HS2	Computer Scientist and Chartered Project Manager	BIM Strategy Manager at High Speed 2 (HS2)	BIM Consultant at Transport for London (TfL)
Int-3	Digital Built Britain (BIM) Advisor at a software provider	Design Engineer	Manager of the Crossrail BIM Advancement Academy	Chair of the Asset Data Dictionary in the UK. Member of the UK BIM Task Group
Int-4	Research Associate in Construction Law group in Higher Education	Chartered Architect and Chartered Project Manager	Significant policy and industry expertise	Secretary General in the Association for Consulting Architects (ACA), Advisor for Digital Catapult
Int-5	Digital Lead in Cities & Development and Aviation at a consulting firm	Chartered Engineer	Manager at the Heathrow Expansion project	Expert Mappers Panel in Infrastructure at Greater London Authority
Int-6	Associate Professor in Project Management and Economics	Royal Institution of Chartered Surveyors (RICS) and Association of Chartered Certified Accountants (ACCA)	Senior Cost Engineer for Translink JV at the Channel Tunnel Project	N/A
Int-7	Innovation Director, Thames Tideway	Chartered engineer	Digital Innovation at Thames Tideway,	Member of i3P; Advisory to Centre for Digital Built Britain; BIM Task Force; Infrastructure Client Group

			Crossrail and London 2012.	
Int-8	Research and teaching. Higher Education	Architect and academic.	Research - Avanti	Leader of Research & Innovation at major industry body.

Appendix B

Table 2: The six sub-units of the embedded case study: UK construction infrastructure projects.

Major UK infrastructure projects	Project dates	Type of project	Digital innovation	Literature sources (excluding interviews)
Channel Tunnel (CT)	1985-1994	Rail infrastructure	Separate modelling solutions for 3D design, cost management and procurement	Pöttler (1992); Genus (1997); Arup (2004); Pollalis and Georgoulias (2008).
Heathrow Terminal 5 (T5)	1999-2008	Airport building	Efforts to consolidate digital tools such as CAD in an online 'single-model environment' and recognition of 'hybrid practices'	Davies et al. (2009); Harty and Whyte and Lobo (2010); Arup (2006); Davies et al. (2016); Gil et al. (2012).
London Olympics 2012	2005-2012	Sports facilities	Application of developments from CT and T5 on technology support and knowledge management about digital innovations	Davies and Mackenzie (2014); Davies et al. (2014); Thiel and Grabher (2015).
Crossrail	2008-2021	Rail infrastructure	Integration of digital tools such as Building Information Modelling (BIM) through online Common Data Environments (CDE)	DeBarro et al. (2015); Dodgson et al. (2015); Arup (2012); Pelton et al. (2012).
Thames Tideway	2012-2023	Water disposal infrastructure	BIM as contracted deliverable. Team will hand over a digital copy of the infrastructure asset, along with the physical version	Gaunt (2017); Morgan (2020); Tideway (2021).
High Speed Two (or HS2)	2017-2026	Rail infrastructure	Integration of BIM with virtual reality aiming to develop a digital twin of the rail	Zahiroddiny (2020)[1]; HS2 (2019; 2021).

[1] Personal communication