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How Digital Information Transforms Project Delivery Models

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Abstract

This study articulates how increasingly pervasive digital information transforms project delivery models. It builds on and extends the literature on innovation and knowledge codification, analyzing London's evolving digital innovation ecosystem across 15 years of industry/government initiatives and infrastructure megaprojects. Findings suggest profound and ongoing changes in digitally enabled project delivery models. Novel contributions are: first, to identify new generations of integrated solutions; second, to articulate changes in supply chains and relationships with owners, operators, and end users; and third, to recognize the growing importance of digital workflows and analytics, rather than documents. There are implications for project management practice and scholarship.

Keywords

digital information, infrastructure megaprojects, project delivery models, integrated solutions, innovation ecosystems, digital maturity

Introduction

Computational devices are now used in all aspects of project delivery. Moore's law correctly anticipated the exponential, rather than linear, growth in computing over the past 50 years, based on Moore's (1965) observation that the number of transistors per square inch on integrated circuits was doubling every year. In the 1960s, computer use in projects involved specialists batch-processing tasks on dedicated, room-sized supercomputers (Morris, 2013). Since then, increasing capability to manipulate and store digital information has been achieved on progressively smaller, cheaper devices—from supercomputers to desktop personal computers, laptops and tablets, and mobile and wearable devices. Brynjolfsson and McAfee (2014) note: "The Cray-2 supercomputer (introduced in 1985) and the iPad 2 tablet (introduced in 2011) had almost identical peak calculation speeds. But the iPad also has speaker, microphone and headphone jack [two cameras, Wi-Fi, and] GPS receiver, digital compass, accelerometer, gyroscope and light sensor" (p. 50). It costs less than a thousand dollars (the Cray-2 cost US$35 million in 2011 dollars) and is "smaller, thinner, and lighter than many magazines" (Brynjolfsson & McAfee, 2014, p. 50). Computers are now over 33.5 million times more powerful than they were in 1965 (MPA, 2015), with many project professionals having their mobile phones within arm's reach at all times throughout the day (MPA, 2015). Digital information becomes increasingly pervasive with such widespread, cost-effective availability of powerful computational devices in project delivery.

The question arises: *How does the increasingly pervasive use of digital information transform project delivery models?* In organizational research, models classify approaches so that they can be studied and provide heuristics to managers (Baden-Fuller & Morgan, 2010); thus, a "project delivery model" describes the underlying rationale behind a project delivery approach, relating to project deliverables; supply chains; and relationships with owners, operators, and end users, where these are mediated by incentive structures, procurement methods, stage-gates in delivery processes, standards used, and client communication. The organizational consequences of the *physical* product are well considered in project management research (e.g., in literature on modularity and structural complexity), but there has been relatively little attention paid to the increasingly important role of the *digital* information that accompanies the exponential growth in computing power. There is insufficient attention given to the important question of how increasingly pervasive digital information transforms project delivery models.

To address this question, a new approach is needed. Where uptake of computers has been described in the project

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management literature, it has usually been considered as a before/after contrast. Thus, Morris (1997) contrasts early scheduling applications run in batches on large mainframe computers with computer-aided design and expert system applications becoming available on desktop personal computers in the 1980s, writing: "Suddenly, the promises of computerized project management began to become a reality" (p. 189). In more recent work, Levitt (2011) characterizes a shift between project management 1.0 and 2.0. His work describes the before/after of a significant shift away from projects like the mid-20th-century U.S. Navy Polaris project—through which project management was developed as the tracking of changes to baseline plans (Morris, 2013)—to project management today, in which project managers expect to be able to engage in a different way, much faster, monitoring and updating information in real-time, through more intuitive interfaces (Levitt, 2011; Whyte & Levitt, 2011). Rather than conceptualizing transformation from a variance perspective, as a single before/after contrast, an alternative approach is to take a process perspective to articulate the direction and set of transitions, associated with ongoing change.

This approach is taken here in a study of the evolving digital innovation ecosystem in the London megaproject ecology, focusing on 15 years of industry/government initiatives, experience of digital delivery in megaprojects, and the growing links across the ecosystem. The next section describes how this study builds on recent literature on innovation and knowledge codification, before the following section introduces the case, research approach, and data collection and analysis methods. The findings section then summarizes, first, the UK industry/government initiatives developing new incentive structures, procurement methods, stage-gates, standards, and client communications for digital delivery; second, the experience of infrastructure megaprojects in relation to project delivery models and use of digital delivery; and third, the growing links between initiatives and megaprojects in achieving digital maturity within an evolving digital innovation ecosystem.

The study is important because it suggests profound and ongoing changes to digitally enabled project delivery models. It finds substantial work by practitioners to accommodate the rapid rate of innovation in computational devices and to identify and benefit from new opportunities of increasingly pervasive digital information. What projects deliver is changing: No longer is the project deliverable a physical product and associated services; it is now also digital information. The discussion section articulates new generations of integrated solutions emerging as digital and physical interact in these deliverables of megaprojects. It describes digitally enabled project models changing supply chains and relationships with owners, operators, and end users. It extends understanding of knowledge codification in projects by showing how digital workflows and analytics, rather than documents, are becoming central to project organizing. Articulating how the increasingly pervasive use of digital information transforms project delivery models, the article ends by suggesting new research directions and implications for project management practice and scholarship.

Background: Innovation and Knowledge Codification

To provide a background to the empirical study, this section sets out extant understanding of how project delivery models are changing and reasons why digital information is transformative in the literature on innovation and knowledge codification, with a particular focus on prior work on infrastructure megaprojects. This motivates the study by suggesting empirical questions about how increasingly pervasive digital information transforms project delivery models.

Innovation in Delivery Models

Across the infrastructure sector, the dynamics of innovation has led to different forms of delivery (Cacciatori & Jacobides, 2005; Gann, 2000), beyond the well-established project delivery models of "management contracting" and "design-build." Over the past decades, various forms of public-private partnerships (McKinsey, 2014) have developed alongside more collaborative approaches, for example, *partnering* (Barlow, 2000; Scott, Levitt, & Orr, 2011), *integrated project delivery* (Lahdenperä, 2012), and *alliancing* (Davies & Hobday, 2006; Flyvbjerg, 2014). Attention is drawn, in this literature, to projects in their historical and organizational contexts, and to the new challenges of systems integration and delivery of integrated solutions.

Megaproject Delivery Models in Context. All projects are situated in historical and organizational contexts (Engwall, 2003). UK megaprojects in the 1980s, 1990s, and early 2000s were overdue and over budget, until a radically new project delivery model was proposed for Heathrow Terminal 5 (T5), involving a collaborative approach to the contractual and organizational relationships between the client and contractors (Davies, 2017). Davies (2017) draws attention to the role of the London megaproject ecology in fostering subsequent learning across megaprojects, where the "expanding network of individuals, teams, contractors and clients working on these projects and circulating between them has helped to establish London's thriving megaproject ecology and worldwide reputation for innovative project delivery models" (p. 124). Such megaprojects in and around London include High Speed 1 (the Channel Tunnel rail link), Heathrow T5, London 2012 Olympics, Crossrail, Thames Tideway Tunnel, and High Speed 2 (HS2).

Scholars have examined individual megaprojects in this London megaproject ecology as leading exemplars; for example, in their study of Heathrow T5, Gil and Tether (2011) identify the use of a progressive design approach to manage risk and enable flexibility; Whyte, Lindkvist, and Jaradat (2016) use the case of the London 2012 Olympics to articulate processes involved in the hand-over of digital information to operations; and Dodgson, Gann, MacAulay, and Davies (2015) draw attention to the systematic approach to innovation on Crossrail, where this has been subsequently implemented through a broader industry infrastructure innovation platform (Davies, 2017).

Within this megaproject ecology, there is a digital innovation ecosystem. In the innovation literature, the term *ecosystem* brings with it a focus on "the evolution of networks of interconnected actors towards new states" (Autio & Thomas, 2014, p. 206). The megaproject is a mode of organizing that involves many firms and other stakeholders (Brookes, Sage, Dainty, Locatelli, & Whyte, 2017), with digital innovation crossing the boundaries of firms, projects, and industries (Lobo & Whyte, 2017) and innovation processes requiring decision making that spans the private and public sectors (e.g., Barlow & Köberle-Gaiser, 2008). Such studies provide some indications of how infrastructure delivery models are changing, and suggest the importance of interconnections across projects in an evolving innovation ecosystem.

Systems Integration and Integrated Solutions. In both projects and firms, new systems integration challenges arise as modularity enables greater outsourcing of design as well as manufacturing (Brusoni & Prencipe, 2011), and as firms leverage the benefits of modularity to enable economies of scale in associated services (Salonen, Rajala, & Virtanen, 2018). Davies and Mackenzie's (2014) work on the London 2012 Olympics finds that systems integration takes place at different levels within the megaproject, with the client and its delivery partner involved at a meta-systems integration level, and contractors involved in integration at the systems level, with "clearly-defined interfaces and buffers between and within individual component systems" (Davies & Mackenzie, 2014, p. 787). As project deliverables change, megaprojects themselves have different relationships with owners, operators, and end users. Operations can also become a service that can be delivered by the firms associated with the delivery project (Alderman, Ivory, McLoughlin, & Vaughan, 2014). Thus, research examines how complex projects extend beyond the duration of project delivery as they are "incorporated into the business interest of participating actors over much longer period of time" (Ruuska, Ahola, Artto, Locatelli, & Mancini, 2011, pp. 657–658).

With the long-term involvement of suppliers in the delivery of services (Alderman, Ivory, McLoughlin, & Vaughan, 2005; Brady, Davies, & Gann, 2005), there is integration of design, finance, construction, operation, and maintenance (Carpintero, 2015). Integration is understood to extend what projects deliver beyond products, to show how "integrated solutions" can combine products and services as a deliverable to long-term operators (Brady et al., 2005). For the firms associated with complex projects, an "integrated solutions" approach involves competing for a new position in the value stream, not as a move downstream into services, but rather as a strategic position spanning manufacturing and services (Davies, Brady, & Hobday, 2006) with increased customer focus (Brady et al., 2005). Cacciatori and Jacobides (2005) chart an experimentation process in which these firms explore such new strategies within a wider innovation ecosystem.

Software brings previously separate activities together (D'Adderio, 2001, 2003), automating workflows and creating new forms of interdependence (Kache, Kache, Seuring, & Seuring, 2017). It transforms innovation processes (Dodgson, Gann, & Salter, 2002, 2005), propagating innovation across the different organizations involved in the digital delivery of projects (Boland, Lyytinen, & Yoo, 2007; Harty, 2005). Industry commentators suggest that integration will be a key feature of digitally enabled project delivery models. A senior executive in a leading technology supplier, when asked to predict changes to the industry over the decade from 2012 to 2022, drew attention to the role of building information modeling (BIM), stating: "Most traditional iconic project delivery models will still exist, but strongly influenced by integrative strategies. In CM-at-risk [construction management-at-risk], for example, a GMP [guaranteed maximum price] will be more robust because of the predictive qualities of BIM. Plus, there will be stable, repeatable integrated project delivery models" (McGraw-Hill, 2012, p. 30). Yet there has been insufficient theoretical attention to the implications of digital information for project delivery models involving systems integration and integrated solutions.

From Documents to Data: Knowledge Codification in Project Delivery

Since the invention of the Gutenberg printing press in the 15th century, codified knowledge has been associated with printed documents. In both firms and projects in the 20th century, such documents became central to organizing. They were "not simply instruments of bureaucratic organizations, but rather are constitutive of bureaucratic rules, ideologies, knowledge, practices, subjectivities, objects, outcomes, even the organizations themselves" (Hull, 2012, p. 251). Yet, digital information has become transformative beyond well-established notions, such that in the information society (Borgman, 2000), information and communication technologies are increasingly convergent (Mansell, 2007) and personal computing increases the codification of knowledge (Steinmueller, 2000). For example, Kallinikos (2006) argues: "Computation constitutes a substantial part of the task infrastructure of organizations as software code" (p. 2). Information production and processing become seen as taking place through digital artifacts that are embedded in "wider and constantly shifting ecosystems" (Kallinikos, Aaltonen, & Marton, 2013, p. 357).

Digitally Enabled Project Delivery. Projects are information processing systems (Winch, 2010, drawing on Galbraith, 1977), where the information that is processed in projects is increasingly digital and organized in engineering and project management information management systems, with links to participating firms' enterprise resource management systems. Table 1 draws on the literature to summarize characteristics of digital information in projects as shareable, accessible remotely, searchable, and updatable. Infrastructure megaprojects now generate millions of digital records in models, drawings,

Table 1. Four Characteristics of Digital Information and Their Implications for Integration in Project Delivery Models

Characteristics of Digital Information	Description	Implications for Integration in Project Delivery Models
Shareable	Digital information can be shared, copied, edited, and moved without loss of quality. Copies have the same quality as the original, and hence, there is no loss of information (Rahman, Sarker, & Bignall, 1999)—unless (and this matters for infrastructure) the file is compressed or becomes corrupted, or cannot be opened or read using available hardware and software.	Building information models reduces transaction costs (Baddeley & Chang, 2015), meaning that information can be easily shared, both across the supply chain during delivery and across stakeholders (Gerbert et al., 2016). It can be worked on by multiple engineers and managers (Love, Liu, Matthews, Sing, & Smith, 2015), suggesting that BIM can act as a catalyst for "future proofing" public-private partnerships and enabling the successful management of an asset throughout its life cycle.
Accessible remotely	Access to digital information is not dependent on knowing where the information is physically stored. Data can be stored in the cloud or on dedicated servers at another location, and can be accessed and used remotely.	Through the internet and intranets, digital information can be used for engineering decision making across remote design offices in geographically distributed international supply chains. Information that was once available on paper can now be easily reviewed from the screen of a device.
Searchable	Digital information can be aggregated, linked, and searched. Dashboards can be used in aggregating and integrating this information for reporting and stakeholder management, and new information can be generated by recombined data streams to allow for new kinds of analytics.	There are time savings associated with BIM use on projects (Bryde, Broquetas, & Volm, 2013). There is significant opportunity to "mine" digital data on projects, to better understand the consequences of decisions.
Updatable	Digital information can be updated in "real time:" Dashboards of information can give direct access to summary information about the status of sensors or the completion rate of drawings on a project.	This is no longer an offline report, but rather a direct window onto the state of the project. However, as many different versions of digital information may be stored, this requires good version control to ensure that the latest versions are always used, and that engineers can track back to particular engineering decisions or the status of an operating system at a particular point in time.

geographic information systems (GIS), and asset databases (Whyte, Stasis, & Lindkvist, 2016). As well as technical information, megaprojects engage with streams of information on scientific foundations and underpinning conditions and on business objectives and the commercial context (Merrow, 2014). The increasing digitization of project delivery is associated with an increasing "professionalization" of the delivery client: New technologies for approvals and workflow monitoring become associated with new occupational groups, new kinds of professional accountability, and a greater integration across professional roles (Jaradat, Whyte, & Luck, 2013).

Project Delivery and the Evolving Digital Ecosystem. General purpose technologies, associated with "long waves" of change across sectors, pervade and revolutionize all sectors of industry (Freeman & Louça, 2001). Megaprojects that deliver physical infrastructure, such as dams, airports, railways, and stations, may take decades to build and may be operated and maintained for decades or even hundreds of years. As digital information pervades their delivery, they are brought into contact with a sector in which the rate of innovation is exceptionally high. Brynjolfsson and McAffee (2014) comment on the exponential growth in computing power, arguing: "there is no period in time when cars got twice as fast or twice as fuel efficient every year or two for fifty years. Airplanes don't consistently have the ability to travel twice as far, or trains have the ability to haul twice as much. Olympic swimmers don't cut their times in half over a generation, let alone a couple of years" (p. 42). The differing rates of change associated with industrial innovation can be discussed through the notion of "clockspeed" (Carrillo, 2005; Fine, 1998),[1] where the exceptionally high clockspeed of digital innovation implies a high rate of change in applications. Benefiting from general-purpose digital technologies thus requires accommodation of this high rate of change as it pervades industries with a lower clockspeed. This is not a one-off transition. Kane, Palmer, Nguyen-Phillips, Kiron, and Buckley (2017) argue that organizations reach digital maturity by becoming able to "systematically prepare to adapt consistently to ongoing digital change" (p. 5).

Thus, to address the main research question, "*How does the increasingly pervasive use of digital information transform project delivery models?*" this review of extant literature raises questions that motivate the empirical study: How are new project delivery models developed within a digital innovation ecosystem? How does increasingly pervasive digital information affect integration in project delivery models? How does it alter what projects deliver; their supplier interactions; and relationships with owners, operators, and end users?

Methods

As digital information becomes increasingly pervasive, this study draws on work on innovation ecosystems (Autio & Thomas, 2014), and in particular on digital innovation ecosystems (Kallinikos et al., 2013), to characterize the evolving digital innovation ecosystem in London megaproject ecology. It traces the organizing practices and connections through 15 years of industry/government initiatives to develop digitally enabled project delivery models and learn from the experience of digital delivery in megaprojects. As discussed as follows, in relation to case selection, data collection, and data analysis, the approach is interpretive, drawing broadly on practice-based and process-based research traditions (Langley, 1999; Pettigrew, 1985, 1995; Pettigrew, Woodman, & Cameron, 2001; Walsham, 1995) to develop theoretical insights about how digital information is transforming project delivery models.

Research Design

The research is designed as an embedded case study of the evolving digital innovation ecosystem in London, with a focus on the links across two units of analysis: industry/government initiatives (Avanti, BIM Task Group, and Digital Built Britain) and infrastructure megaprojects (Heathrow T5, London 2012, Crossrail, and HS2).

The justification for focusing on London relates to its status as a pioneering ecosystem for the development of these new digitally enabled project delivery models. First, initiated by Heathrow T5, there has been a set of significant infrastructure megaprojects in and around London, through which there has been substantial learning within a megaproject ecology as discussed above (all of the initiatives and megaprojects studied are developed through project offices and institutions in London). Second, there has been substantial government and industry focus on digital delivery over the past 15 years. Though this builds on earlier initiatives to increase the use of information technologies in construction (Gann, 2000), the digital innovation ecosystem has grown substantially over the past 15 years, moving to center stage and attracting significant investment, with the UK government as a client mandating use of building information modeling (BIM) on major projects from 2016, and professional institutions acknowledging its centrality to their practice—for example, through the Institution of Civil Engineers (ICE) State of the Nation 2017: Digital Transformation (ICE, 2017) and the Royal Institute of British Architects (RIBA) revised plan of work. Third, London is now influencing international practices in digital project delivery. Digital standards and processes developed in this setting are becoming influential internationally. For example, the British Standards (BS) 1192 standards are being developed into International Standards (ISO) 19650 standards. International initiatives improving the extent to which digital information is used in project delivery draw on ideas developed in and around London (e.g., a workshop in London led to a recent World Economic Forum report on BIM [WEF, 2018]).

Data Collection

Data are summarized in Tables 2 and 3. These were collected through a series of research projects, the first of which examined the use of a single digital model environment at Heathrow T5, and as part of this work collected data on and engaged with the Avanti Programme. The second set of data was collected through work on technology use in global projects. A research team was established, through which data were collected and analyzed on the UK BIM agenda, London 2012, and Crossrail. Since 2015, data collection has been less formal, and has involved ongoing interactions with Digital Built Britain and the new set of megaprojects in the London area. Data on the UK government and industry initiatives are shown in Table 2. Data on digitally enabled practices in the delivery of four infrastructure megaprojects are shown in Table 3.

Project delivery models are organizing practices that are distributed in ways that are difficult to capture through more locally and temporally bounded studies. An in-depth and reflective engagement with the field is thus seen as a source of research strength (Kanuha, 2000; Tedlock, 1991), with the author developing, over time, a close and ongoing relationship with the field of study, becoming a member of associated communities and seeking to develop narratives of project delivery model transformation that are credible and can be confirmed by participants in the field.

Data Analysis

For this article, data analysis is informed by the emphasis of process studies on events, actions, and choices, using temporal bracketing and narrative analysis strategies (Langley, 1999). Preliminary work to analyze the dataset involved developing a timeline of events associated with digital information initiatives and digital practices on megaprojects over the 15 years. Table 4 shows the main government and industry initiatives in the London megaproject ecology and the delivery of the infrastructure projects bracketed into five-year periods.

Using these five-year periods as a guide, links and interconnections between events in the data in Tables 2 and 3 were identified and situated in relation to the literature. This data analysis is iterative, and builds on deep engagement with the context, and dataset, over an extended period. I had previously coded many of the datasets, such as those for Heathrow T5 and London 2012 Olympics, in detail with attention to digital practices. On Heathrow T5, this initially involved 41 codes, which were then grouped and aggregated into major descriptive themes such as learning, digital tool use, digitization, and project management approaches. As I became familiar with the challenges of digital delivery of megaprojects, my analyses informed the protocols for data collection on later megaprojects, and data collection and coding focused on areas of change in digital practices and areas in which theoretical saturation had not been reached in the earlier studies.

There is now a cluster of related digital initiatives and megaprojects being developed in parallel in London. As the

Table 2. Data Sources and Industry Engagement Related to Digital Transformation Initiatives in London and the UK

The Avanti Programme (2002–2007)	
Meetings, semi-structured interviews, published and internal documentation	Attending three meetings of the UK government Avanti Programme; four semi-structured interviews in 2003–2004; 43-page final report; 352 pages of documentation from the Avanti Programme
The UK BIM Agenda (2010–2015)	
Published documentation	BS1192 standards; BIM Task Group and related websites and social media
Meetings and unpublished documentation	Attending meetings of the UK BIM Forum, with representation from all of the member professional bodies and institutions, meeting quarterly from 2012 to 2017 and receiving their agendas and minutes; attending ICE BIM conference and Bentley "Year in Infrastructure" conference in 2014 and 2015; sitting on two related government/industry working groups, on client deliverables, and hand-over of data to the clients
Research meetings (*hand-over of digital data from projects to operation)*	Three-hour workshop with key construction industry participants held at the university; two informal interviews with major projects; one recorded interview and two meetings on data hand-over and operations with participants of another large capital asset
Semi-structured interviews	12 semi-structured interviews with leading clients and supply chain as identified by ICE in 2010 (present at all interviews)
Published documentation	40 industry reports, international standards, and practical guidance books
Public presentations	Two days of industry events, taped with audio and PowerPoint slides available for analysis
Research meetings (*owner and operator use of BIM)*	Meetings of the Infrastructure Client Working Group; meetings to set up in-depth study with owner and operator (a set of interviews was conducted); workshop to validate findings with a wider set of key owners and operators across the sector to understand owner perspectives
Digital Built Britain (post-2015)	
Published documentation	BS1192 standards; BIM Task Group and related websites and social media; report on Digital Built Britain; National Infrastructure Commission report on "Data for Public Good"
Public presentations	ICE BIM conference and Bentley "Year in Infrastructure" conference
Meetings and unpublished documentation	Attended series of workshops to shape Digital Built Britain agenda; advisory board meetings for the ICE State of the Nation 2017: Digital Transformation; member of the Digital Built Britain R&D committee (2017); member of the Health and Safety Executive (HSE) group that developed BS1192-6; expert group for Centre for Digital Built Britain Research Bridgehead (2018–present)

megaproject ecology grows in scale and complexity, while remaining highly interconnected, it becomes more difficult to isolate single digital initiatives and megaprojects. Hence, my discussion of recent and ongoing work acknowledges overlapping and parallel work, as well as the dense interconnections between digital initiatives and between megaprojects. I have sought to represent the agency and choices available in different time frames, and the differences across time. In order to address potential "retrospective bias," the analyses have revisited documents, field notes, and interview transcripts that were collected in these three five-year periods as interpretations were developed. My own personal archive of research materials has been invaluable in revisiting earlier initiatives, as institutional archives that are available online have become pruned, edited, and rebranded to suit later agendas.

Findings: The Evolving Digital Information Ecosystem

The underlying rationale for project delivery has been questioned and debated in the digital innovation ecosystem associated with the London megaproject ecology, in response to the exponential growth in computing power that is enabling pervasive use of digital information on megaprojects. There were three main industry/government initiatives that shaped these efforts, explicitly seeking to develop new incentive structures, procurement methods, stage-gates, standards, and client communications that support digitally enabled project delivery. Table 5 sets out key events and activities involved in accommodating increasingly pervasive digital information in the past 15 years, summarized in five-year periods; these are discussed in more detail in the following subsections, which describe industry/government initiatives, the learning about digital delivery on infrastructure megaprojects, and the links developed across the evolving digital innovation ecosystem in achieving digital maturity.

Industry/Government Initiatives

Three industry/government initiatives—the Avanti Programme, BIM Agenda, and Digital Built Britain—bring stakeholders (including professional institutions, individuals,

Table 3. Data Sources and Industry Engagement Related to Digital Delivery of Infrastructure Megaprojects

Heathrow Terminal 5	
Research meetings	Seven hours of setup meetings as part of research team: site visit to Heathrow T5 hosted by Laing O'Rourke, presentation on project, hosted visit from Director Laing O'Rourke, two-hour meeting with and presentation to British Airports Authority (BAA) project managers and Laing O'Rourke at Heathrow
Semi-structured interviews	50 semi-structured interviews as part of a research team (present at 41 of these interviews, with 22 as sole researcher, with particular focus on digital delivery)
Internal documentation and site visits	Visit to roof subproject; 100+ pages of internal documentation on digital delivery and roof sub-project; shared videos and photos of practices
Public presentations	Attended presentation by BAA project manager
London 2012 Olympics	
Research meetings	Three-hour meetings with two or more of the key stakeholders in the Olympic Delivery Authority (ODA); two-hour setup meeting; two-hour meetings discussing emergent findings; author attended three hours of site training to obtain a pass to access the project offices on site
Semi-structured interviews	21 semi-structured interviews: 16 with project participants involved in hand-over of digital data as identified by ODA in 2011 (17 participants, as 2 at one interview), 4 in 2012, also interviewed legacy owner in 2013 (present at 16/21 interviews)
Internal documentation	267 pages of guidance for project participants on data hand-over procedures and 21 PowerPoint slides
Public presentations	Three hours of evening events disseminating findings from the Olympics; taped with audio and PowerPoint slides available for analysis; one-hour presentation by the ODA chairman; and four other presentations of design and digital technologies at the ODA, and their delivery company CLM (a joint venture by CH2MHill, Laing O'Rourke, and Mace), attended by members of the research team; one-day conference about London 2012; access to learning legacy website
Other engagement with the infrastructure project	Three weeks in CLM on information management in 2007, five days in CLM in 2012 analyzing intranet documents/processes on digital delivery
Crossrail	
Research meetings	15 days of work in the Crossrail offices to review documentation and prepare findings from previous research for presentation to project managers. Interview and workshop related to configuration management
Internal documentation	482 pages of reports and relevant internal documentation
Public presentations	Access to learning legacy website
Other engagement with the infrastructure megaproject	Consultant role on external BIM advisory board for the project; supervised an engineering doctorate (EngD) student in the information management team
High Speed 2	
Research project meetings and interviews	One-day "engagement" meeting for academics in Birmingham; visits to three project offices; seven informal conversations with HS2 staff; two interviews
Public presentations	Attended four presentations on HS2 and/or digital delivery in HS2
Other engagement with the infrastructure megaproject	Consultant role on the external BIM advisory board for the project from 2014

government departments, firms, and megaprojects) together across the public and private sectors. They represent many person-years of effort, much of it voluntary, to develop template processes for the use of digital information on infrastructure projects in the United Kingdom, with new guidance on procurement and new contractual clauses, revision of stage-gate processes, and development of information standards to enable provision of digital information as a project deliverable. They are summarized as follows.

The Avanti Programme. This £5 million government program was industry-led (funded through the Department for Trade and Industry), focusing on "an approach to collaborative working that enables construction project partners to work together effectively" (Building Research Establishment, 2018). Information standards were developed to improve the consistency of the data developed in design. A significant overlap in the people involved in the Avanti Programme and those involved in setting up the information management strategy for Heathrow T5 meant that this initiative involved an update to the associated BS1192 standard (collaborative production of architectural, engineering, and construction information: code of practice [BS1192: 2007]) based on the Heathrow T5 experience. Avanti developed handbooks and toolkits and involved onsite mentoring to improve the use of digital information. It was a forerunner to the UK BIM Agenda, and informed this

Table 4. A Timeline of Government/Industry Initiatives and Infrastructure Megaprojects in the Digital Innovation Ecosystem in London

		2004–2008					2009–2013					2014–2018				
Three government and industry initiatives	Avanti Programme	■	■	■	■											
	BIM Task Group							■	■	■	■	■	■	■		
	Digital Built Britain												■	■	■	■
Four infrastructure megaprojects	Heathrow Terminal 5	■	■	■	■	■										
	London 2012 Olympics		■	■	■	■	■	■	■	■						
	Crossrail							■	■	■	■	■	■	■	■	■
	High Speed 2												■	■	■	■

Note. The grey shade conveys the information on when these different projects and initiatives were active.

Table 5. A Timeline Summarizing the Focus in Industry/Government Initiatives, Learning in Associated Infrastructure Megaprojects, and Links Across the Evolving Digital Innovation Ecosystem

	2004–2008	2009–2013	2014–2018
Focus of industry/ government initiatives	*Collaborative use of digital information:* Avanti Programme upskills companies and projects.	*Structured asset information:* BIM Task Group; vendors work with project to provide licensing models across firms.	*Connections with outcomes:* BIM "level 2" mandated on publicly funded projects in 2016; BIM "level 3" on operations and use.
Learning to use digital information in individual infrastructure megaprojects	Heathrow T5 implements "single model environment" as part of a collaborative project delivery model. Plans for London 2012 Olympics to use of a single, closely controlled multidisciplinary model.	London 2012 Olympics integrates digital information across the venues and park for hand-overs to games and legacy owners. Crossrail sets up information management processes and monitors first-tier suppliers' delivery of digital information.	Crossrail nears completion and seeks to collate digital information as a deliverable for hand-over to long-term operators. The roadmap for implementation of BIM in HS2 is set out.
Toward digital maturity: Links across the evolving digital innovation ecosystem	Heathrow T5 single model environment informs setup of London 2012 Olympics and BIM Task Group. Transport for London (TfL) enables app developers to build digitally enabled services for end users using its data.	Crossrail takes lessons from the London 2012 Olympics and seeks to implement processes from the BIM Task Group. Initiatives consider a wider range of data formats, including data capture from laser scans and mobile devices as well as structured asset information.	Use of BIM level 2 on infrastructure megaprojects. Crossrail informs the next generation of infrastructure megaprojects (Tideway, HS2, Hinkley C, Crossrail 2) through industry-level innovation initiatives. Initiatives consider the emergence of cheaper Virtual Reality (VR)/ Augmented Reality devices, sensors, and robots.

later work by progressing both standards for information management and the advocacy for the importance of those standards.

The UK BIM Agenda. In this initiative, the UK government led the development of new processes for digital delivery. A government BIM Task Group website was set up (available from 2012 to 2017), indicating the focus on "sector modernization." Associated activities involved lawyers examining contracts, and insurers, financiers, clients, and their supply base coming together to discuss new project delivery models. The Construction Industry Council (CIC) group of professional institutions worked with the government to progress and disseminate the activities of the task group through a BIM forum. The initiative changed project delivery models by altering the following:

Incentive structures: The UK *Government Construction Strategy* (Cabinet Office, 2011) announced that the government was going to require building information modeling (BIM) to be used on all of its projects by 2016. The UK government sought to use its role as a client for infrastructure projects (rather than its regulatory powers) to mandate the use of BIM on major projects from 2016 in order to address challenges of cost, value, and carbon. The implications for project delivery models were clear from the start as industry and government set out to deliver this mandate.

Procurement methods: Professionals tasked with implementing the strategy through the UK BIM Agenda were aware of the different maturity levels present across the industry, and the journey toward more digital ways of working. In the early days, the BIM Task Group worked closely with the Ministry of Justice to map and understand the inefficiencies in extant public delivery processes as the basis for designing new processes. The recommendations of the BIM Task Group changed the scope of services of different parties and set out new roles, such as the BIM coordinator, with implications for the tender documents used to procure a supply chain to deliver a project. The CIC (2013) BIM Protocol is a legal agreement that can be incorporated into professional service appointments and construction contracts as a simple amendment, setting out the new responsibilities for the delivery of digital information. Alongside this are a best practice guide for professional indemnity insurance, scope of services for the role of information management, and Employer Information Requirement and new British standards (BS) and publicly available specifications (PAS), including guidance on BIM (BSI, 2007, 2013, 2014a, 2014b, 2015, 2018) and documentation on construction prequalification questions (BSI, 2017, pp. 32–33).

Stage-gates in the process: To describe the project life cycle, template stage-gate models of project processes provide the supply chain with a shared cognitive framework for understanding the status of the project and how much needs to be done before completion, fostering common understandings across the industry, as well as being associated with the contract and structuring payments to consultants, contractors, and subcontractors. In the United Kingdom, there is a wide number of template stage-gate models used in different infrastructure sectors, with, for example, the UK building sector using an RIBA Plan of Work since 1963. The collaborative use of digital information challenges the stages identified in these models as it requires more attention to information generation earlier in the process. In the CIC BIM Forum, there was substantial discussion of the need to rationalize and update these stage-gate models to better reflect this. The most radical transformation took place to the RIBA Plan of Work, which is a standard template process for building delivery. The RIBA Plan of Work was rewritten and in 2013, changing from stages labeled A–F to define stages numbered 0–7 (0: Strategic Definition, 1: Preparation and Brief, 2: Concept Design, 3: Developed Design, 4: Technical Design, 5: Construction, 6: Hand-over and Close Out, 7: In Use). The government required information exchanges to take place at stages 1–3 and 6. There were changes in the activities associated with each of the stages, where the stages in earlier plans of work around production information and tender documentation are altered in recognition of the fact that these activities now occur earlier in the digital delivery process. There was also a shift from representing the plan of work as linear to representing it as circular.

Common standards for using digital information: Underlying the above is a substantial effort to develop new, industry-wide standards to support the delivery of digital information as well as physical assets. A set of these standards underlies BIM level 2 and includes specific requirements for BIM, use in operational phase, hand-over of information, security-mindedness and safety (BSI, 2007, 2013, 2014a, 2014b, 2015, 2018). These standards are important as digital information is generated and used across multiple technology platforms and across multiple firms; it may also need to be reused decades in the future, when the infrastructure is being used but the digital technologies available to access the information have changed. This initiative also championed standards with software vendors and in the international open standard and open-source software communities such as Building Smart (http://buildingsmart.org/).

Client communication: To clarify the exchange of digital information between the delivery supply chain and the client, a set of "data drops" was articulated, showing how, as documentation, nongraphical and graphical information grows, and then how, at particular stage-gates, information is provided to the client (this was mandated for public clients, but major private clients also adopted it). These stage-gates are typically also associated with staged payments to the suppliers. A template process of articulating Employer Information Requirements and then addressing these through a BIM Execution Plan was developed and presented to the CIC BIM Forum.

Digital Built Britain. The development of BIM level 3 anticipated by the UK government's 2016–2020 Construction Strategy (Infrastructure and Projects Authority, 2016) and described as part of a "Digital Built Britain" strategy (HM Government, 2015) will require more extensive change in procurement, as such extensive collaborative use of digital information is not possible under current procurement models. Since 2014, there has been an extended discussion about the scope and focus of BIM level 3, with some arguing for a focus on operations and use, rather than project delivery. In late 2017, the initiative moved out of government and a Centre for Digital Built Britain was set up to take this agenda forward.

Digital Delivery of Infrastructure Megaprojects

Increasingly available computational resources enable project managers and engineers to access digital dashboards, analytics, and workflows through widely distributed and multifunctional devices. Across the four infrastructure megaprojects considered below, Heathrow T5, London 2012 Olympics, Crossrail, and HS2, there is a growing convergence of technologies associated with BIM, GIS, process modeling, communications, survey information, and the use of sensors for smart infrastructure, with new experimentation with hardware such as drones or augmented reality devices on projects. Table 6 summarizes the project delivery models and approach to digitally enabled delivery in these megaprojects.

Each megaproject implemented an integrated software solution in which an interconnected set of applications is accessed through a common database and user interface. Across these megaprojects, there is a significant increase in the extent and

Table 6. Project Delivery Models and Digitally Enabled Delivery in Infrastructure Megaprojects

	Project Delivery Models	Digitally Enabled Delivery
Heathrow Terminal 5	Long-term owner-operator BAA acted as the delivery client for the project and used the T5 Agreement to share risks and rewards.	Single model environment, held by BAA with access for first-tier suppliers, used to coordinate and manage interdependencies across subprojects. The design software was provided by Autodesk through a reseller.
London 2012 Olympics	The megaproject delivery client, the Olympic Delivery Authority (ODA), worked with a delivery partner, CLM. Contracts for the major venues used a collaborative contract, New Engineering Contract (NEC) 3, option C (a target contract with activity schedule).	Contracts were out before the digital strategy was developed, and so different subprojects used different technologies, and then files were converted for archiving and for hand-over by CLM and passed to ODA for onward transmission to games in 2012 and long-term owners and operators.
Crossrail	Crossrail acts both as the megaproject delivery client and delivery partner. The three major tunneling contracts used a collaborative contract (NEC3, option C). Different parts of the line (which will be known as the Elizabeth Line in operations) will have different long-term owners and operators, with hand-overs to Transport for London and Rail for London.	A central information strategy was put in place, with GIS, BIM, and asset management data being aggregated and stored at project level. There is a strong partnership with Bentley Systems: All contractors were trained in use of data, and the quality of information they developed was monitored.
High Speed 2	HS2 is the megaproject delivery client, with CH2 M, Atkins, and SENER as delivery partner in Phase 1, with contracts in Phase 1 using a collaborative contract (NEC3, option C).	The ambition is to receive information in standard formats rather than to specify data, and to use standard processes. There is a BIM roadmap associated with the project.

variety of project information and process maturity. The amount of information generated is growing, leading to new challenges in sorting, analyzing, storing, and retiring data. There have hence been substantial efforts to standardize data formats and create metadata to categorize and search databases. While Heathrow T5 termed its digital system a *single model environment* (SME), in both Heathrow T5 and the London 2012 Olympics, unstructured text in documents was still central to organizing practice. In Crossrail, searchable digital databases and the hierarchy of asset information become more salient, with the quality of data provided by contractors more systematically and regularly monitored and evaluated.

Heathrow Terminal 5. Heathrow Terminal 5 (T5) was a £4.2 billion infrastructure project at Heathrow Airport, London, with the terminal opening in 2008. This project was delivered before the BIM mandate and, as much of the learning from Heathrow T5 was captured in the Avanti Programme, it can be seen as a precursor to the BIM mandate. The project received a particular stimulus for introducing new ways of working following the near-disaster when a tunnel collapsed under construction on a previous project, the Heathrow Express, in 1994. The inquiry had revealed inadequate documentation of construction work in progress. On Heathrow T5, the government and the banks were expecting the British Airports Authority (BAA) to demonstrate its ability to manage such a large project. John Egan (1998), who was chief executive of BAA at the time, was also advising the government. At Heathrow T5, the innovations included collaborative contractual arrangements with suppliers through the T5 Agreement and also introduced a single model environment (SME)—a precursor to BIM—as a repository for all the information relating to the project. Yet the hardware and software available in the early 2000s when Heathrow T5 was in design and construction were not adequate, and there were substantial frustrations in terms of the time it took to upload or read files from the shared server.

London 2012 Olympics. The London 2012 Olympics was an £6.7 billion infrastructure delivery project in the east of London, with the project starting in 2005, when London won the games bid, and the venues and Olympic park opening to host the games in 2012. There were additional costs for running the games and for conversion to legacy uses. This project was delivered before the BIM mandate and because of the tight time scales for delivery, some contracts were already agreed upon when the program-wide design information management strategy was being formulated. For this reason, established teams used their own preferred software at the project level and there was a very large integration effort toward the end of the project to get the information translated into consistent formats for games and legacy uses. The information management team within the Olympic Delivery Authority (ODA) delivery partner grew substantially, to service the significant need for document control, especially as the supply chain was asked for information in two different formats, and it was found that the document submitted was not always accurate, or the same in the different submissions. This project was innovative in the development of robust processes for receiving digital information from the supply-chain and in preparing this information for hand-over.

Crossrail. Crossrail is a £14.8 billion infrastructure project to deliver a new railway across the heart of London, with the first trains scheduled to run in 2019. This project was developed during the BIM mandate and this influenced the development of information management strategy. The project developed a strategic relationship with a software provider, Bentley Systems, and trained all its subcontractors through the Bentley Academy. It held a dataset centrally: The requirement to deliver asset information was written into contracts with the supply chain. Techniques were developed for monitoring the quality of information supplied by contractors and for more rapid cycles of reporting. Experiments were conducted with tablet computers and augmented reality on Crossrail construction sites. The dataset was larger than on previous projects, with three million records in asset databases, one million model and drawing records, and quarter of a million GIS records (Whyte, Stasis, et al., 2016). To manage changes and deliver value, significant effort was put into configuration management[2] and the development of asset information for handover to the eventual owners and operators.

High Speed 2. High Speed 2 (HS2) (Phase 1) is currently funded as a £24.3 billion infrastructure project (including contingency) to deliver a railway from London to Birmingham. It is scheduled to open in 2026. This project is taking a different approach from Crossrail, and instead of seeking to integrate through particular proprietary software, it is seeking to integrate through particular open data formats and standards. This requires greater maturity in the use of digital information across the supply chain, and in the open standards available to support the project. A major motivation for the use of BIM is the productivity gains in delivery, although it is recognized that there may be downstream benefits in operations and maintenance.

Achieving Digital Maturity

Over the 15 years studied, an evolving digital innovation ecosystem has developed in the London megaproject ecology, with many links between the industry/government initiatives and the megaprojects. In the face of exponential rates of change, project managers in megaprojects engage with initiatives in this digital innovation ecosystem to understand the direction and set of transitions associated with ongoing change and to learn, adapt, implement, and customize their use of pervasive digital information.

The challenge of "thinking into the future" becomes a concern for project managers in all of the megaprojects studied, as they seek to address the different clockspeed of digital innovation and infrastructure delivery. For example, a project manager explains the reason for avoiding a late decision to embed radio-frequency identification (RFID) tags in the concrete: "Megaprojects last five to ten years typically and technology time scales are 18 months for big cycles of change, so we play a game which we call last responsible moments in safeguarding, so what we do there is I look at my program of work and I ask the question: What's the last responsible moment at which I can make a decision around any of these high-risk technology decisions?" (Heathrow T5, interview, two years before opening). Another project manager discussing future opportunities for digitally enabled remote access said: "If you think of the way now an iPad, the power within something like that and . . . maybe there is no need, I don't know, but you can see there being a potential for things like iPad and mobile communications of that type to people who work in the field who are out all day. That strikes me as something to think about in the future, the next one of these, what the next big program is" (London 2012 Olympics, interview, 16 months before opening). As progressively smaller, cheaper devices become available, project managers have to consistently adapt, engage with, and consider implementation of new digital technologies through the process of delivery, identifying, and taking opportunities to learn across megaprojects.

As a result of this ongoing process of change, there is a growing volume, complexity, and convergence of the heterogeneous set of digital information used, across the megaprojects studied. Heathrow T5 is a seminal project in which asset information (design models in BIM and more large-scale data held in GIS) was shared with first-tier suppliers through the single model environment (and involved email communications). In later projects such as Crossrail and HS2, asset information is shared and also combined with a wide range of heterogeneous data. These may include data captured from physical infrastructure (e.g., from laser scanning, photogrammetry, video, embedded sensors, or smartphones); systems engineering tools (e.g., to capture requirements and trace these through the delivery process); communications (e.g., structured data, social media); computation and visualization (numerical information in engineering simulations, scheduling, logistics, and optimizations; virtual and augmented reality, 4D modeling, etc.); and fabrication and assembly data (robotics, drones, 3D printing, off-site and near-site automation). As project data grow increasingly heterogeneous and complex, so too does the potential for greater monitoring, integration, and enrichment, with greater visibility across the supply chain, and with end-user use of operational data (for example, as the operator Transport for London [TfL] gave app developers access). Such integration of project information opens new opportunities for value creation, and also raises new challenges (e.g., around the security of systems and access management).

The focus of the digital innovation ecosystem is not on shaping the underlying technologies (which are general-purpose computational devices developed outside of the megaproject ecology), but rather on developing the rationale for a digitally enabled approach. The ICE State of the Nation 2017: Digital Transformation (ICE, 2017), for example, emphasizes the changes in behaviors and productivity and the potential for digitally enabled projects to create resilient infrastructure. Owners and operators of infrastructure are experimenting with new forms of relationship with the supply chain, with, for example, the UK Construction Client Working Group launching an "alliancing" approach, where the first-tier suppliers work closely with owners and operators across multiple projects. The leader of this initiative argues: "Key features of these

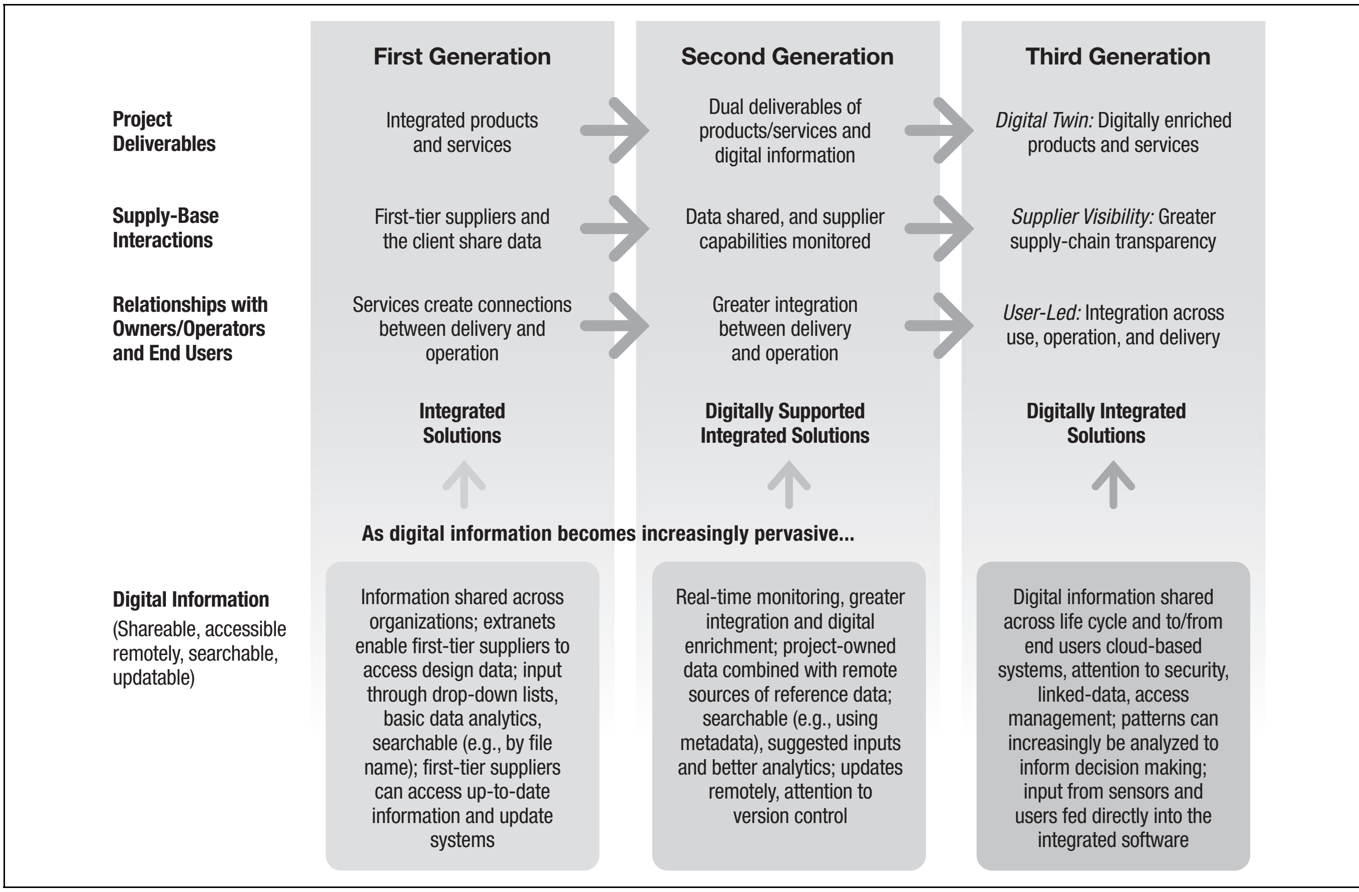

Figure 1. Three generations of integrated solutions made possible by increasingly pervasive digital information.

new delivery models include direct relationships with critical suppliers and common production systems. An emerging trend is for the traditional role of the general contractor to be replaced by an integrator" (Murray, 2016, p. 75). Through this digital innovation ecosystem, megaprojects in London are engaging with such thought leadership to inform their development of new digitally enabled project delivery models.

Discussion: Digitally Enabled Project Delivery Models

Across the megaprojects studied, digital information has become used with the ambition to foster collaboration, to deliver structured asset information, and to better consider project outcomes (as in Table 5). The pervasive use of digital technologies is transforming project delivery. It is changing what projects deliver: No longer is the deliverable a physical product and associated services; it is now also digital information. The use of digital technologies is also changing how projects are delivered: There is greater sharing, remote access, searching, and updating of information with visibility across the supply chain and with owners, operators, and end users. This section draws on the findings of the research to articulate the new generations of integrated solutions emerging with these changes to project deliverables; the new digitally enabled project delivery models that are altering supply chains and relationships with owners, operators, and end users; and the growing importance of digital workflows and analytics, rather than documents.

Three Generations of Integrated Solutions

Though the sharing of digital information facilitated the development of the integrated solutions identified by Brady et al. (2005), this study suggests that, as digital information becomes a deliverable, new generations of integrated solutions are emerging that require firms to combine, not only manufacturing and services (Brady et al., 2005; Davies, 2004), but also technology and data analytics. Figure 1 synthesizes literature and empirical findings to show the project deliverables; supplier interactions; and relationships with owners, operators, and end users across the generations of integrated solutions; and how this relates to digital information and how it is used on projects.

Digitally supported integrated solutions arise as digital information becomes a deliverable, and as digital information becomes mobilized for systems integration, with real-time monitoring of suppliers and greater integration between delivery and operations. As a project client, the UK government sought, through the work of the BIM Task Group, to improve datasets on national infrastructure. Digital information has the

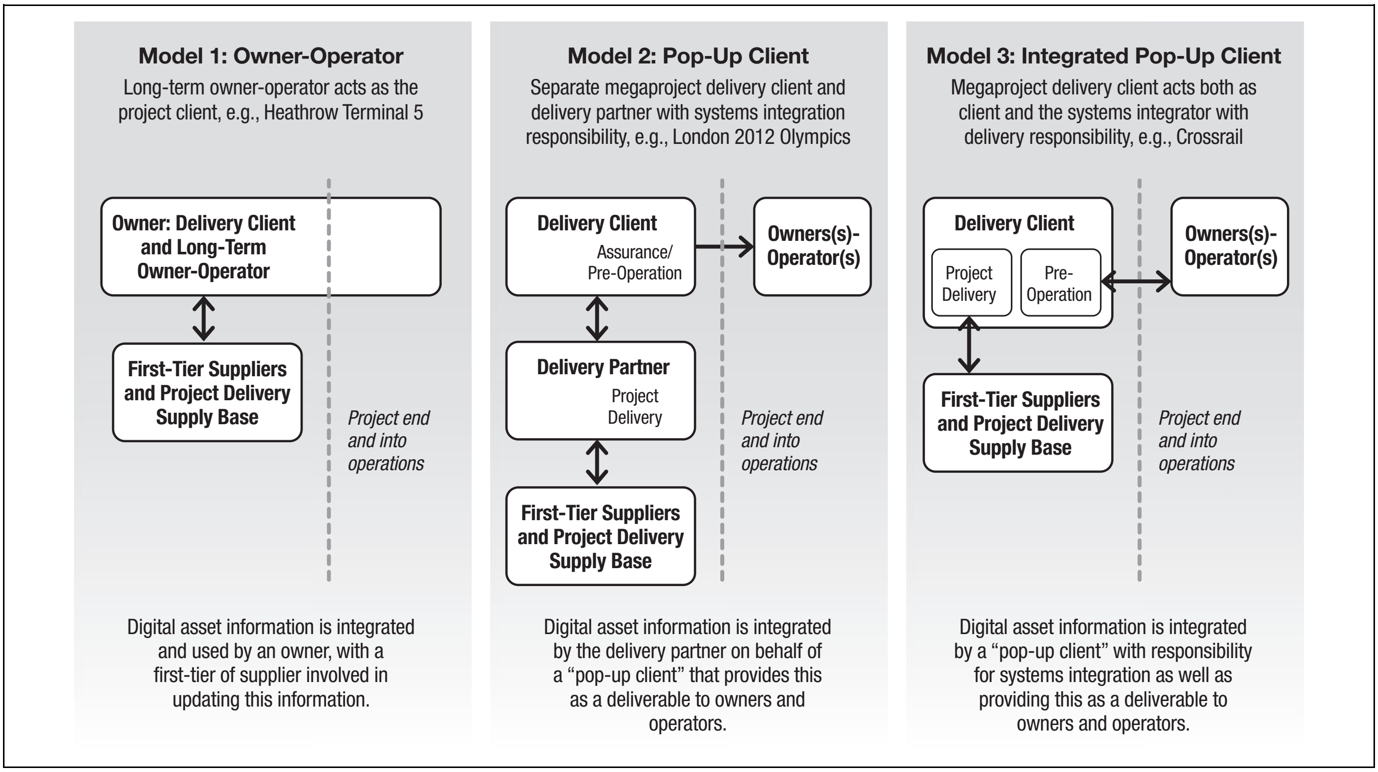

Figure 2. Different digitally enabled project delivery models, showing interactions across the project end into operations as digital information becomes a project deliverable.

potential to bring about a more substantial integration across use, operations, and delivery. As digital information becomes increasingly pervasive, there are indications of a further transition to digitally integrated solutions, in which the project deliverables involve a “digital twin,” where there is supplier visibility and integration with use as well as operation and delivery. Information about and from users of infrastructure is increasingly influencing project investment decisions. This is a tighter integration than was achieved through the merging of capital expenditure (capex) and operational expenditure (opex) headings to consider total expenditure. In organizations such as TfL, operational outcomes such as reduced congestion and increased capacity may be achieved by changing user behavior or by building new infrastructure. The information available regarding usage and asset operation is thus influencing decisions regarding not only maintenance and repair but also new investment. Such changing practices alter the context in which associated firms position themselves and compete, as the characteristics of digital information lead to greater integration across the supply chain and with owners, operators, and end users. Digital information brings into focus not only the owner-operator as customer, but end users as this customer’s customers.

The Process of Experimentation in Digitally Enabled Project Delivery Models

Digital information makes new collaborative project delivery models more viable, beyond the well-established project delivery models of “management contracting” and “design-build.” Figure 2 shows three different configurations of supply-chain and downstream relationships involved in the transfer of digital information as a deliverable from the project into operations. These new models are centered on the (1) owner-operator, (2) pop-up client, and (3) integrated pop-up client. They are enabled and mediated by the structures, methods, and standards developed through industry/government initiatives, addressing significant challenges in integrating digital information from the supply-base as a deliverable and suggesting different relationships between delivery and operations.

As shown in Figure 2, the first model is that of the *owner-operator*. In Heathrow T5, the long-term owner-operator, BAA, took responsibility for integration and directly contracted with the first-tier suppliers through a collaborative contract (the T5 Agreement). BAA held the integrated software and collated the dataset of digital information about the physical assets during the delivery phase. The second model is that of the *pop-up client.* Where there is a separate megaproject delivery client (set up as a proxy for the long-term owner during the delivery phase) and delivery partner, there are more layers of responsibility for systems and data integration. On the London 2012 Olympics, systems integration has been characterized by Davies and Mackenzie (2014). This study finds that responsibility for the integration of the digital information is also distributed, with different software and processes used in the venues and games, and significant integration effort by the delivery partner before handover to the pop-up client responsible for delivery into operations. The third model is that of the *integrated pop-up client*. In Crossrail, for example, the delivery client itself assumes the systems integration responsibilities taken by the delivery client in the second model, including responsibilities for data integration from the supply chain, and for the integrated software. Thus, the delivery client has two sides, as it has the responsibilities of delivery and acts as a client in the pre-operation phase. These dual responsibilities led Crossrail to move beyond sharing data to monitor suppliers to a more integrated approach with greater real-time supplier visibility.

The infrastructure megaprojects studied suggest different possible relationships between delivery and operation phases. As well as delivering physical assets to owners and operators, on projects such as Crossrail, the project team is delivering, and is contractually obliged to deliver, digital asset information. In the first model, the long-term owner-operator directly contracting with first-tier suppliers and through them the broader project delivery supply chain has a vested interest in the use of digital information for operation and maintenance. Thus, in the case of Heathrow T5, data collated during delivery were used in operations. In the second model, the London 2012 Olympics, a delivery client or pop-up client serves as a proxy for the long-term owner during the delivery phase, with a separate delivery partner taking on the responsibility to integrate and collate the digital information from suppliers and transfer it to the delivery client, which then transfers it to long-term owners and operators. In the third model, in a megaproject such as Crossrail, the delivery client has responsibility for identifying and interacting with the supply base as well as for relationships with long-term owners and operators. In relation to digital information as a deliverable, they become responsible for integration and collation, and then for the transfer of this database to the long-term owner. These models differ in seemingly important ways, such as in how they allocate responsibilities for integrating digital asset information from the supply chain and transferring it into the organizations involved in operations; however, further empirical research is required in order to take us beyond observing and describing these differences and toward identifying how these differences shape performance.

Beyond Documents

The findings suggest a fundamental shift in the nature of organizing, away from the documents that are central to bureaucracy, to new ways of constituting the task infrastructure of projects through structured digital information, workflows, datasets, and analytics. Digital information can be shared, accessed remotely, searched, and kept up to date in new ways. Documents are still used, but there are now millions of digital records associated with megaprojects (Whyte, Stasis, et al., 2016). There is a growing focus on digital workflows to populate digital datasets and on how such data can be searched, accessed, tracked, reorganized, and analyzed using asset identifier codes. Work to develop industry-wide approaches to structuring digital information was developed through all three industry/government initiatives studied, with substantial work to develop and update standards. There is an increasingly problematic and less linear relationship between knowledge and digital information than is captured in the idea of "codification." The observations in this study hence extend understanding of knowledge codification in projects, supporting Kache et al.'s (2017) finding of workflow automation and new forms of interdependence, and the work of Kallinikos (2006) on how the task infrastructure of the organization is constituted as software.

Conclusions, Implications, and Further Research

This study articulates, for the first time, how increasingly pervasive digital information is transforming project delivery models. As the computational devices used in all aspects of project delivery are becoming progressively smaller and cheaper, digital information is changing what projects deliver, with information becoming itself a deliverable. Digital information is also changing how projects are delivered: enabling greater sharing, remote access, searching, and updating of information with visibility across supply chains and with owners, operators, and end users. This study found the digital innovation ecosystem in the London megaproject ecology to be a mechanism for the development of new digitally enabled project delivery models, involving industry/government initiatives to changes incentive structures, procurement methods, stage-gates in delivery processes, standards used, and client communication, as well as experiments and learning from digital delivery on infrastructure megaprojects.

Three novel contributions are made to project management scholarship. First, a contribution is made to work on integrated solutions, by identifying new generations (integrated solutions, digitally supported integrated solutions, digitally integrated solutions) as products and services become digitally enriched, with greater supply-chain transparency and integration across usage, operation, and delivery. Second, a contribution is made to work on project delivery models, characterizing three models as (1) owner-operator, (2) pop-up client, and (3) integrated pop-up client, and describing how these address changing supply chains and relationships with owners, operators, and end users in digitally enabled project delivery. Third, a contribution is made to understanding knowledge codification in projects by highlighting the growing importance of digital workflows and analytics, rather than documents. The work extends the discussion of computer uptake in the project management literature beyond a single before/after contrast, describing the dynamics and interconnections of these organizing practices to articulate an open-ended set of transitions, where new opportunities arise for projects to benefit from further development of digitally enabled project delivery models as the evolving digital innovation ecosystem grows in maturity. As digital information becomes increasingly pervasive, these contributions have implications for project management practice and scholarship, suggesting new directions for research.

Implications for Project Management Practice

The study finds that practitioners do substantial work to accommodate the rapid rate of innovation in computational devices and to identify and benefit from new opportunities of increasingly pervasive digital information. The implications for project management practice are that, to achieve digital maturity, project managers need to address the different clockspeeds of developments in IT and infrastructure to "systematically prepare to adapt consistently to ongoing digital change" (Kane et al., 2017, p. 5) through accommodating change and "safeguarding future possibilities" in the digital delivery of megaprojects. The importance of this, as well as the rationale for a progressive design approach to manage risk and enable flexibility (Gil & Tether, 2011), is suggested by the manager at Heathrow T5's insight, that "megaprojects last five to ten years typically and technology time scales are 18 months for big cycles of change." Advising managers to approach digitally enabled project delivery models as involving ongoing change, is quite different to the recommendations that arise from before/after contrasts. It acknowledges the continuous and non-linear growth in computational power observed over recent decades.

Implications and New Directions for Scholarship

The contributions and limitations of this work suggest new directions for research for project management scholars. It introduces ideas of digitally enabled project delivery models, digital innovation ecosystems, and digital maturity into project management scholarship. Rather than being a variance approach, the approach taken here moves beyond before/after contrasts to articulate the direction and set of transitions in project delivery models, while leaving open the potential for the many future (and not yet thought of) choices and developments that may arise in response to exponential growth in computational devices. Further research could build on the concepts and approach introduced in this study to enrich our understanding of these emerging forms of project delivery, of how projects interact with digital innovation ecosystems, and of the issues that arise for the associated firms.

For scholars of innovation in project-based firms, the research suggests new directions to extend understanding of digitally enabled integrated solutions. The changes propagated through government/industry initiatives and megaprojects in the digital innovation ecosystem have implications for the strategies of associated firms. Firms seeking to offer digitally integrated solutions may need to combine outsourcing and capabilities in systems integration, operational services, business consulting, and/or vendor financing (Davies et al., 2006) with new technological capabilities to provide and use integrated software solutions and analyze data. Future work could look at the strategies and positioning of particular project-based firms and the new technology and data analytic capabilities. Though Lobo and Whyte (2017) show how firms seek to align megaproject strategies to their existing capabilities, there is a need for further research to extend understanding of how firms use their access to and ability to use digital information to position themselves in the value chain.

Scholars with interest in knowledge codification in projects could extend understanding of the shift from knowledge codification through documents, to knowledge generation through digital analytics. We need to know more about the convergence of such digital information and the project practices in which it is shared, accessed remotely, searched, and updated. Further research is important as the growth in computing power not only increases the extent of digital information, but new techniques for the distribution of computation across devices also enable wider use of computationally intensive simulation. Fan, Han, and Liu (2014) describe the paradigm shift in statistical methods associated with "big data," which suggests a new range of automation of expert tasks. This paradigm shift is bringing new computational capability into project management, with increasing use of statistics and search and pattern-matching across vast datasets providing new opportunities to transform project governance and project delivery processes.

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Notes

1. Fine (1998) introduces the term *clockspeed* into the analysis of industries. Though this is not explicitly stated, his notion of an industry clockspeed seems to be an analogy with a computer, where the clockspeed refers to the rate of processing cycles (now measured in billions of operations per second on mobile devices).
2. A process for maintaining product integrity through ensuring consistency across requirements, asset information, and physical assets.

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