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Managing change in the delivery of complex projects: Configuration management, asset information and 'big data'

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Abstract

As we enter an era of 'big data', asset information is becoming a deliverable of complex projects. Prior research suggests digital technologies enable rapid, flexible forms of project organizing. This research analyses practices of managing change in Airbus, CERN and Crossrail, through desk-based review, interviews, visits and a cross-case workshop. These organizations deliver complex projects, rely on digital technologies to manage large data-sets; and use configuration management, a systems engineering approach with mid-20th century origins, to establish and maintain integrity. In them, configuration management has become more, rather than less, important. Asset information is structured, with change managed through digital systems, using relatively hierarchical, asynchronous and sequential processes. The paper contributes by uncovering limits to flexibility in complex projects where integrity is important. Challenges of managing change are discussed, considering the evolving nature of configuration management; potential use of analytics on complex projects; and implications for research and practice.

Keywords: Complex projects; Configuration management; Change; Asset information

1. Introduction

Digital technologies radically transform project delivery. Twenty years ago, Morris described the evolution of project management as closely related to developments in systems engineering, modern management theory, and the evolution of the computer (Morris, 1997: p.2). Today, mobile hardware, cloud computing and integrated software are becoming used for storage and retrieval, automated search, and prototyping and simulation functions. As such technologies are adopted in project-based industries, their use is breaking the mould of established approaches to project management, enabling more rapid and agile forms of organizing (Levitt, 2011; Whyte and Levitt, 2011). Up-front project planning, using multiple layers of work breakdown structures, became established by the 1960s in the management of large complex projects (Morris, 1997: p.44). New digitally-enabled approaches are emerging in industries, such as consumer electronics, software development, biotechnology and medical devices, that operate in dynamic and less predictable situations in which plans need to be updated and modified during project delivery (Whyte and Levitt, 2011). In these, data analytics and visualization using large digital data-sets – along with rapid, informal interaction and exchanges of information – provide the basis for more responsive, flexible and real-time decision-making (Levitt, 2011).

The information used to make decisions in the management of complex projects is generated and stored digitally. Complex projects are a set of projects that share particular defining characteristics: they are high-tech, capital intensive engineering projects that are of a significant scale, relatively long duration, and require firms to work collaboratively across firm boundaries in project delivery (Davies and Hobday, 2006; Hobday, 1998; Miller et al., 1995). Such projects deliver complex product systems, such as aircraft, experimental facilities and

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railways. Their delivery requires systems integration capabilities, as complex product systems are designed and integrated through a network of component and sub-system suppliers (Davies and Mackenzie, 2014; Davies et al., 2009; Hobday et al., 2005). Within these projects information about complex product systems is developed across multiple firms, involving diverse professions and trades, as these organizations interact through the digital systems.

A starting point for our work is the observation that, as we enter an era of 'big data', asset information is becoming a project deliverable. *Data* are unprocessed, often described as "unorganized facts" (e.g. Faucher et al., 2008: p. 55), while *information* is interpreted and presented to inform in a given context. Owners seek to use asset information to achieve sustainable and safe performance of complex systems through the life-cycle. An asset may be an assembly, sub-assembly, or component, but is the smallest unit maintained by an owner. The term 'asset information' is used to describe information about an asset, which may include the provenance, part types and serial numbers, design life, maintenance schedule, and design rationale for sub-systems or components. As data gets reused across the life-cycle, sets of data and information become combined and can be mined, interpreted and used in new ways. The UK government, for example, is, as a client for built infrastructure, requiring project teams to deliver asset information through building information modelling (BIS/ Industry Working Group, 2011); and seeks to aggregate and combine data-sets, connecting them with Smart City and Smart Grid initiatives as part of a strategy for Digital Built Britain (UK Government, 2013).

Established approaches for managing change on projects use configuration management, a systems engineering approach with origins in the mid-20th century. In its original form, configuration management is characteristics of what Levitt (2011) describes as 'project management 1.0.' It involves hierarchical, sequential and asynchronous processes; managing change against a baseline. Its use focuses attention on assets as *configuration items*: sub-systems or components that have value to the organization, in which changes will often have systemic consequences on the function or layout of other items within the product structure and hierarchy. The baseline is an agreed description of one or a number of assets at a point in time, where the current configuration of a complex product system is described by the latest baselines plus approved changes.

New practices of managing change in complex projects might be expected as we enter an era of 'big data', in which internal and external data-sets become linked and asset information becomes a project deliverable. Morris argued that:"*rigorous change control is fundamental to good project management*" (Morris, 2013: p.126). Poor change control is one of the issues that limits managers' ability to execute viable project plans (Pinto, 2013). Others see projects, themselves, as information processing systems (e.g. Winch (2010) drawing on Galbraith (1973, 1977)). As project management information systems (Braglia and Frosolini, 2014) are increasingly used, altering the pace and complexity (Shenhar and Dvir, 2007) of projects, there are challenges to the: "*heavy formality of several of the techniques to manage large-scale, one-time, non-routine projects*" (Morris, 2013: p. 133). Here, Morris, like Levitt, points to software projects, in particular, as rebelling, using agile forms of management, through small projects with close developer-customer relationships.

The aim of this research is to articulate how changes in assets and the associated asset information are managed in the delivery of complex projects as we enter the era of 'big data.' This is done by analysing leading practices in three organizations: Airbus, CERN and Crossrail. Each of these organizations delivers complex projects; relies on digital technologies to manage a large volume of information; and uses configuration management to establish and maintain the integrity of the complex product system and associated information (see Table 1). Airbus is an aircraft manufacturer, operating in the aerospace industry and engaged in production of commercial and military aircrafts, with long-term projects to design and develop new aircraft designs and bring them into operation. Its headquarters are in France but the supply-chain is global, with the assembly of each plane involving thousands of companies and millions of parts. CERN is the European organization for nuclear research and the largest particle physics research establishment in the world, with 21 member states, 6 observer states and more than 80 collaborating countries. Its mission is to provide scientists from all around the world with tools to study the building blocks of matter and the origins of the universe. Crossrail is the largest construction project in Europe, with 14.8bn funding, delivering a new 100 km rail route with 10 new stations and a tunnel through central London connecting 40 stations. It has a complex supply-chain involved in delivery with more than 1,300 contracts.

Table 1
Background of organizations studied, and their industries.

	Airbus	CERN	Crossrail
Industry	Aerospace design and manufacturing	Nuclear research infrastructure	Civil engineering and railway infrastructure
Background	Leading aircraft manufacturer of commercial and military aircrafts, with a substantial international supply-chain.	Largest particle physics research establishment in the world with tunnels and particle accelerators	Design and construction of new railway across London with tunnels and 37 stations
Relationship to projects	Long term internal projects to design and manufacture new additions to the fleet, such as the A380, integrating sub-systems and components and delivering to customers.	Experienced project owner, managing supply-chain delivering accelerators such as the Large Hadron Collider (LHC)	Delivery client for a mega-project, the duration of which is 2008–2018, interfacing with future operators of the railway.
Location	France	Switzerland	UK

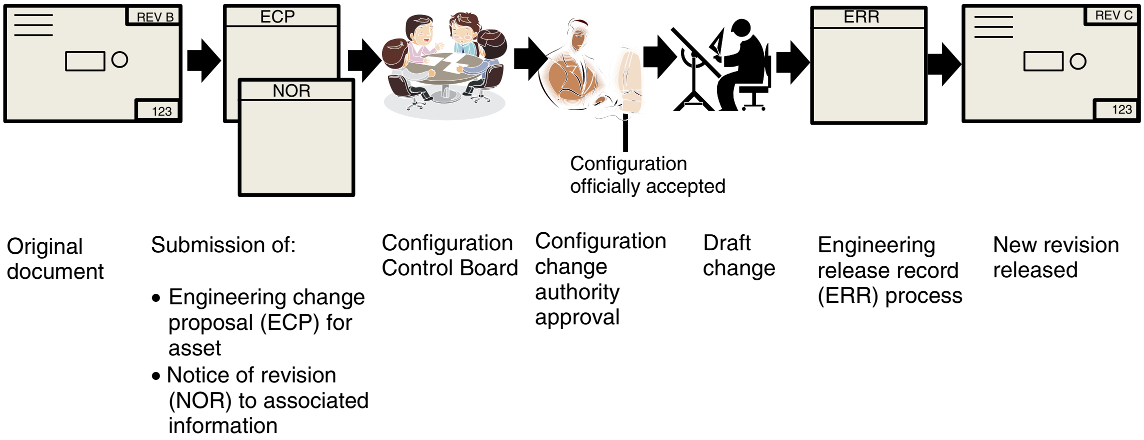

Fig. 1. Standard change process (redrawn from source: DOD, 2013: p. 33, to clarify and explain acronyms, same images of documents and clip art used).

The next section outlines extant research on managing change in delivery, before the following sections describe our research methods and findings. It outlines the development of configuration management techniques; characteristics of an era of big data; and relevance configuration management and big data to Morris' interest in 'reconstructing project management.'

2. Managing Change in Project Delivery

2.1. Development of configuration management techniques to manage change

Configuration management was developed in the 1950s by the US military to control documentation in the manufacture of missiles (Brouse, 2008; Burgess et al., 2005; Gonzalez, 2002). Early documentation on engineering change control, released by the military, clarifies the contractual obligations and role of suppliers. It refers to a product baseline describing the functional, physical and interoperability characteristics of components for testing and operations (DOD, 1978; Military, 1988). Two example change processes, used in the commercial arrangements of acquisition and supply, are provided by the Department of Defense guidance issued in 2013 (see Fig. 1 for one of these, where the other is a variant). As well as change control, the classic approach to configuration management involves the identification of the product structure and configuration items; s*tatus accounting* to determine the configuration of the system at any stage of the lifecycle (Burgess et al., 2003; Kidd and Burgess, 2010) and report on the availability and retrievability of data; and *audit* to verify the consistency of the information (Kidd and Burgess, 2010). The approach has become extensively used in the software industry (Bersoff, 1984; Estublier, 2000; Williams, 2009), and in safety critical systems such as nuclear and aerospace (Burgess et al., 2005; Williams, 2009). It became recognized as an ISO 10007 quality management process in 1995 (ISO, 2003). The presentation, with a man at a drawing board, shows the heritage of this approach in the paper-based processes of the late 20th century; though in the 21st century such processes are supported by digital systems.

The US military describes configuration management's overarching goal as: "*to ensure there is documentation which completely and accurately describes the intended design, the actual product matches the documentation, and there are processes in place so this continues throughout the product's life*" (DOD, 2013: p.10). The ambition is to address the problems which occur in projects due to unchecked changes in one sub-system having wider consequences for other sub-systems of a product (Hameri, 1997); and due to scope creep, where requirements change during the process of delivery (Williams, 2009); providing traceability of product data to understand where problems occur, diagnosing and contributing to recovery (Burgess et al., 2003). A configuration is: "*a generic term for anything that has a defined structure or is composed of some predetermined pattern*" (Kidd and Burgess, 2010: p. 109). An authorization approach is used to control change and there are different hierarchy levels depending on the use of configuration items (Billingham, 2008). A baseline is established: "*wherever it is necessary in the product life cycle to define a reference for further activities.*" (ISO, 2003: p. 4). From an approved baseline, a configuration change authority assesses the recommendation of other representatives to approve, approve with modifications, or disapprove submitted changes based on the: "*total lifecycle impact of the action to include cost, schedule, performance and logistics impact*" (DOD, 2013: p. 27).Thus the processes, procedures and users of the configuration management system play an integral role in maintaining the integrity of information throughout the life-cycle by controlling changes. If users do not follow the process, errors can occur which can cause problems to the product in production and to related information dissemination (Hameri, 1997; Hameri and Nitter, 2002). Researchers of configuration management constantly find the benefits of such a controlled process of change are not always understood or realized by users (Ali and Kidd, 2014; Burgess et al., 2003; Kidd, 2001; Kidd and Burgess, 2010).

The upsurge in the use of digital technologies and flexible team-working bring into question configuration management practices based on documents rather than information (Burgess et al., 2005). Characteristics of 'configuration management' are not stable and fixed but are themselves evolving, to include the life-cycle, agile approaches, and changes to strategy as well as project. For example, after cancelling its configuration management standard MIL-STD-973 in 2000, the US Department of Defense found that it continued to be used in non-standard ways. From 2010 they developed a new standard for configuration management to changes through life using digital systems (Windham, 2012). The interim standard mentions three baselines, with a functional baseline giving system level requirements; allocated baseline giving subsystem or configuration item level requirements; and product baseline giving detailed definition (DOD, 2013: p. 18). There are recent attempts to develop an agile approach to configuration management through a system to accommodate small continuous changes and manage the additional complexity across dispersed teams (Moreira, 2010); and reports suggesting an expanded scope of configuration management, to include enterprise as well as product baselines (Wozny et al., 2014).

2.2. Reuse of information and data linkages in the era of 'big data'

There are rapid developments in digital technologies and an extensive growth in the volume of data stored digitally that affects project delivery. The term 'big data' indicates the use of large heterogeneous data-sets that can themselves be aggregated, and subjected to various forms of analytics to enable patterns in the data to be visualized. While there is not agreement on a precise definition, many writers, across both information science and social science literatures, draw on Laney (2001) to refer to data volume, velocity and variety. *Volume* of data is implied by the term 'big data' and is an issue because there is an increasing extent of data available (Wu and Wu, 2014), with 2.5 exabytes of data created globally each day in 2012 and expectations that the rate of data production will double every 40 months (McAfee and Brynjolfsson, 2012: 62). Yet recent work emphasises characteristics other than volume (Boyd and Crawford, 2012; Kitchin, 2014). *Velocity* relates to the speed of production and of access of data. Advances in computing processing capacity enable data-sets to be engaged with in real-time, or near real-time, rather than 'freeze framed' (Kitchin, 2014) or processed offline. *Variety* refers to the diverse range of data sources and types of data that are combined (Viitanen and Kingston, 2013; Wu and Wu, 2014). On projects this variety can include hierarchically structured data such as models, and unstructured data such as laser scans, videos, sensor data, photos and experimental data. While volume, velocity and variety are generally characteristic of the applications described as 'big data', these applications vary in the extent to which they emphasise one or the other of these characteristics.

Big data represents a paradigm shift, where "*most of our attitudes and behaviours still reflect hierarchical and sequential processing of data*" (Galbraith, 2014). Information is no longer created and used for a single purpose (Constantiou and Kallinikos, 2015). As we enter an era of 'big data', information from projects becomes seen as a project deliverable and used throughout the lifecycle. Organization scholars observe how: "*organizations are swimming in an expanding sea of data that is either too voluminous or too unstructured to be managed and analyzed through traditional means*" (Davenport et al., 2012: p. 22). Different professional users bring their own way of organizing data to understanding it, so early work highlighted a need for indexing strategies that were agnostic to these structures (Laney, 2001: p. 1). Big data is different from 'lots of data' as it is: "*those data that disrupt fundamental notions of integrity and force new ways of thinking and doing to reestablish it*"(Lagoze, 2014: p.4-5). It thus raises a conundrum for science (Lagoze, 2014): how to utilize the benefits of 'big data' while maintaining the validity of data.

Despite ongoing concerns about integrity, many organizations are moving away from asynchronous and reactive decision-making; to the use of predictive analytics for real-time and proactive decision-making. Within the social science literatures on 'big data', analytics is described as a differentiator of organizational performance (LaValle et al., 2011); a source of competitive advantage (Barton and Court, 2012; McAfee and Brynjolfsson, 2012); or new frontier of competition (Floridi, 2012). Here, the challenge of big data has been reframed as one of identifying small patterns (Floridi, 2012) within immense databases, and the use of these to create new value and knowledge. Emerging technologies are associated with this business analytics (Chen et al., 2012); and the way that information is considered is different, as analytics may be used to seek insights from the flow of information as well as its content (Williams et al., 2014). Various text and web mining as well as social network analysis techniques are becoming used to organize and visualize information to understand performance in organizations (Chen et al., 2012; Williams et al., 2014). The many-to-many non-linear data relationships that arise in large and evolving data-sets (Wu and Wu, 2014) lead to challenges in ensuring reliability, which has implications for decision making. Different preferences in recording data can result in diverse representations and relationships that makes it difficult to discover useful patterns (Wu and Wu, 2014). Synthesized information may thus need to be situated in a broader historical context to be used in a predictive manner (Boyd and Crawford, 2011).

The power of flexibly linking asset information with other data-sets is beginning to be realized by owners of complex product systems such as infrastructure. Transport for London has, for example, made data available to customers, and also to engineers, to combine data in new ways to develop new applications.[1] Williams et al. (2014) point to the potential for a census rather than sampling approach to organizational data to be used to assess organizational maturity in the use of project-management. Recent industry reports envision a future in which data-sets are linked and analytics are used predictively, for example to precompute scenarios and inform decision-making (e.g. BIM 2050 Group, 2014). There may be latent applications in complex projects, for example in the use

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[1] See https://www.tfl.gov.uk/info-for/open-data-users/ (Another example is http://data.london.gov.uk/).

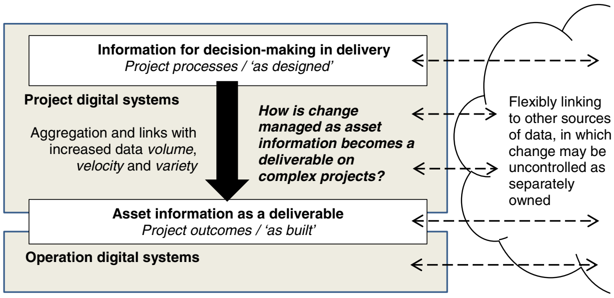

Fig. 2. Context for our research question on managing change as asset information becomes a deliverable on complex projects.

of dashboards as an interface to whole data-sets to evaluate supply-chain performance.

2.3. 'Reconstructing' project management: configuration management in an era of big data

Morris (2013) has an ambition to 'reconstruct' project management by shifting attention from the execution of projects to the management of projects – which includes the definition of the project, the role of the owner or sponsor, and the project context. This wider view is necessary to investigate how change is managed in an era of 'big data' where asset information has becomes a project deliverable. The complex project delivers an asset that is used in operations. As asset information becomes a deliverable, Fig. 2 shows how data-sets become increasingly aggregated and linked in the delivery of the project, with links to external sources of data (e.g. from suppliers, manufacturers and maintainers), and the complex project responsible for managing change in an increasing volume, velocity and variety of data in project digital systems. This anticipates potential new connections, for example between information used in the project and reference schedule and cost data; and between asset information and the owner's enterprise resource planning system.

Digital systems are not homogeneous, but combine networks, servers, and computers with software for different purposes, and from different vendors. They are used in the storage, retrieval, management and manipulation of data; with data management software used to upload, integrate, structure, index and search data, and to manage remote access, security, versions and workflows. Stored data includes files, folders and meta-data; held in a range of specialist software. In projects most of this data is classified and structured, though it can be combined with a variety of sources of unstructured data in projects, which have previously been ignored (Boyd and Crawford, 2011). Where organized for a particular purpose we describe it as information, hence asset information as a deliverable is managed digitally, and reuses the same data-sets that have been used to inform decision-making in delivery.

A major question, raised by the era of 'big data' relates to control and the management of change as digital data-sets cross organizational boundaries; particularly as information about assets gets re-used in operations. In manufacturing and construction industries the use of information through the life-cycle is often referred to as Product Life-cycle Management (PLM) and Building Information Modeling (BIM) respectively. The practical concerns of project managers about control in this context are reflected in the report of a meeting of the Major Projects Association, which in summary notes that: "*Manual uploading of data between software programmes allows better understanding of progress and visibility*" (MPA, 2013: p. 3). In this report there are concerns that project managers feel swamped as the project controls themselves produce massive data-sets. The solutions proposed are manual interventions, to identify key information or manually transfer data.

Configuration management is discussed little in the project management literatures, and where it is mentioned, notably in Morris' work, it is as implemented through the digital systems used on projects. In the move toward the "era of the paperless project", Morris describes configuration management: "*extended to include the configuration of the total project documentation handling process.*" (Morris, 1997: preface, note 4); noting increasing focus on information rather than documents. The Project Management Body of Knowledge Guide likewise refers to the configuration management system as a component of the project management information system, containing versions and baselines for all project documents (PMBOK guide, 2013: p. 28). Standards for asset management likewise indicate this need to manage changes to assets assessing risks and consequences of change. While we know that users resist configuration management processes and these are not fully implemented (e.g. Ali and Kidd, 2014), we know little about how change is managed on complex projects, as we move into an era of 'big data, and asset information becomes used as a project deliverable. We approached our empirical work with a question about how changes in assets and asset information are managed in this context as summarised in Fig. 2.

3. Methods

Using a case study methodology (e.g. Eisenhardt and Graebner, 2007; Stake, 1995; Yin, 1994), we analysed change management practices in the three separate organizations as cases, and then compared and contrasted the findings across cases to develop further insight. The organizations were selected as leading organizations that deliver complex product systems using digital technologies to manage the large volumes of associated information. Data was collected from the three organizations, and their interactions with each other as summarized in Table 2. Our initial contact with participants indicated our interest in examining the transition from an "as-designed" configuration baseline to an "as-built" configuration baseline; as information was delivered to owners and operators. The preliminary analysis was based on a desktop review of leading configuration management activity in through-life engineering and scoping interviews with 1–2 personnel from the CAD management and/or configuration management teams from Airbus, CERN (online) and Crossrail (in-person) as well as a visit to Airbus premises. The scoping interviews used a protocol with starter questions including: How is configuration management defined? What are the processes

Table 2
Sources of data for the individual cases and the comparison across cases.

Organization	Interactions and observations	Associated documentation
Data on each individual case		
Airbus	Online call (2 participants and 2 researchers) and day-long visit to Toulouse (10 participants and 2 researchers); email clarifications.	Presentation discussed in online call (20 pages) and 3 publically available presentations (79 pages).
CERN	Online call and presentation (2 participants and 2 researchers); email clarifications.	Internal documents (23 pages, QA procedure; status report); 2 conference papers (6 pages); and presentation (29 pages).
Crossrail	In person interview (1 participant and 2 researchers) and ongoing collaboration.	Access to internal system and documents on configuration management.
Comparison across cases		
Airbus; CERN and Crossrail	3 hour workshop with 20 participants, recorded in 49 photographs (some video) and notes; email correspondence.	Presentations from the workshop (94 slides).

involved in setting up this configuration management? What is the approach to configuration control? What are the challenges in terms of integration of data from as-design configuration baseline to the as-built configuration? At the end of projects did you find differences between the as-built with the as-designed?

The comparison across cases was facilitated by an afternoon workshop hosted in the Crossrail offices in London. The workshop in Crossrail offices involved twenty participants, with at least two participants from the CAD management and/or configuration management teams within each organization studied. This day was recorded with video; 49 photographs and notes as well as through the distribution of presentation from each organization afterwards (totaling 94 slides from the 3 companies). It was an opportunity for presentations about the context for the research; for feedback of preliminary findings; presentations on configuration management from the three companies and discussion of key theoretical challenges.

Following the workshop we analyzed and iterated a detailed table that compared configuration management practices in the three collaborating organizations, in relation to topics that had arisen in the discussion at the workshop: 1) *background* (e.g. overview, infrastructure type, scope of works, budgets); 2) *lifecycle* (e.g. typical lifecycle duration; development time); 3) *complexity* (e.g. physical assets; asset information); 4) *configuration management motivation* (corporate motivation, industry guidance, teams); 5) *approach and systems* (e.g. lifecycle breakdown, approach, data management, information systems and supporting tool, structure of configuration items; 6) *managing change and change control process* (e.g. change perspective, change control process, conformances and non-conformances); 7) *risks*; *cultural and social issues* (e.g. language, culture). The table we generated was used to visualize the data for discussion in the research team (Miles and Huberman, 1994), to identify salient similarities and differences, and to check details with the collaborating firms. We discussed the findings in this table, which was seven pages long, to identify why all three firms had a strong interest in configuration management and to highlight the similarities and differences. To develop our argument we reorganized our data, bringing it into dialogue with the existing literatures on the management of projects.

4. Findings

The three organizations studied have different levels of experience of configuration management. Airbus has mature processes and systems, with interest in leading development of future systems to manage and control the growing amount of data produced in the delivery of complex products. CERN introduced configuration management in the 1990s (Bachy and Hameri, 1997; Hameri, 1997; Hameri and Nitter, 2002; Hameri and Puittinen, 2003) and are reflecting on their approaches to configuration management, challenges and areas for improvement. As a major project, Crossrail is a temporary organisation, established in 2008. It has a configuration management team and has drawn on industry standards (e.g. ISO, 2003) to rapidly embed configuration management processes in the delivery of asset information. Motivations given for using configuration management in managing change in these settings include the complexity of complex product systems, operational constraints, and the need for valid asset information. The regulated nature of each of the industries (aerospace, nuclear research and civil engineering), mean these organizations all need to be able to track configuration items to be able to revisit designs and comply with future regulation on safety-critical facilities. In Airbus, configuration management is a strategic priority. In CERN and Crossrail, it is an explicit activity that is addressed in organizational strategy using the language of managing change.

4.1. Configuration management in Airbus

As an aircraft manufacturer, Airbus employs around 63,000 people in France, Germany, Spain and the United Kingdom. It has subsidiaries in the United States, Japan, China and India; and the final assembly of aircraft is in France, Germany, Spain, and through a joint venture in China. Customers include commercial airlines. Satisfying their evolving needs requires the design and manufacture of new additions to the fleet. Airbus invests about two billion euros annually in research, development and technology activities. It operates in the highly regulated aerospace industry, in which each aircraft manufactured requires an individual certificate of airworthiness showing it conforms to the approved design, and has the relevant documentation, inspections and tests to ensure it will be safe in operations. Aircraft components have strict definitions that include architectural nature and materials. There are rules on how components are aggregated into sub-assemblies and assemblies to ensure the correct serviceable part is available for every configuration and operating condition.

Configuration management is one of the 14 Airbus key competences, considered in procurement of the supply-chain and included as a requirement in contracts. It is well established in Airbus. There is a Centre of Competence where 80 internal employees and 70 external consultants work to edit methods, process and tools; and a significant broader capability, with more than 8000 professionals with related tasks, including 800 internal and 500 external configuration management professionals.

A motivation for configuration management is the product complexity. It can take more than a decade to develop a new aircraft design. Airbus produces several aircraft families, each with members and versions. No two aircraft are the same as customers can select between variants and the production standard evolves continuously. The number of parts and combinations of solutions grow with product complexity along with the combination of configurations to be managed. Product architecture includes component parts, numbering and links; with 500–1000 concept definitions, with associated solutions and ways to restore previous solutions.

There is a significant *volume* of data, where each aircraft has millions of parts. The Airbus A380 plane has, for example, about 4 million parts, with 2.5 million part numbers produced by 1,500 companies from 30 countries around the world. There is a growing *velocity*, with increasing production rates, and shorter product development lead times. As aircraft design requires careful analysis of performance data, there is also significant *variety*, with product information linked to structured and unstructured data-sets with test results, electrical bonding calculations, requirements from economic analyses, weight distribution, and weight calculations, etc. Configuration management processes have substantial digital support, with six preferred suppliers for configuration management services. However, as the number of data-sets has increased, some information related to the aircraft is no longer well linked. For example, the functional baseline with the initial specifications is not well linked with the technical baseline, within which change is managed once requirements are approved. Instead these are synchronised at a particular point and reset.

In Airbus, a configuration item is seen as “an invariant item in the product structure”, where each configuration item is linked to a design solution. While configuration items stay the same, the engineering baseline, used to design, gives a different view of the product architecture from the manufacturing baseline, which is used to install things, and both are different from the data needed in customer services. It can be difficult to recover a technical functional baseline when a big evolution is done to a standard aircraft, where the interface between different data-sets are not linked which means the source of data is not easily known. A significant milestone is the move between concept and definition phases, where data is moved from a development environment to a production environment, which often involves different data structures. At this point, engineers may be involved in manually updating data, re-numbering data-sets as well as re-defining links.

Before product evolution can take place in the concept stage there is an important “congruency process”, through which engineering and manufacturing agree on product architecture and terminology. A request for a product evolution then involves four stages: *initialization*, which is the change request; *evaluation*, which involves an evaluation study; *investigation*, which involves a modification proposal and consideration of technical, cost, embodiment and production repercussions; and *implementation and closure*, in which there is a full technical repercussions sheet, technical dossier and modifications approval sheet. There are also processes for managing change in product identification, and releasing information from engineering and manufacturing information in the definition stage. All these process involve a final step that verifies the implications of change to the product structure at higher levels within this complex product system; and ensures consistency across all domains (including systems, electrical, test and technical data).

Airbus wants to improve efficiency of the product data management by achieving: *scalability*, through reuse of data; *agility*, through integration of data, and *adaptability*, through flexibility in integrating data changes. Configuration management challenges include:

- *Different product architectures* – Developing agreement between stakeholders in engineering, management and customer services takes a long time. In Airbus’ experience, developing a complete architecture can take up to three years to agree. After the congruence process, the product architecture is the same in both engineering and manufacturing and a bill of materials is produced.
- *A desire to be agile in a highly controlled environment*. The strict and rigid system developed through the congruency process lacks flexibility. Yet, even after the congruency process is complete there are still changes that need to take place based on technology developments and the changing competitive environment that may not have been included in the congruency process.

Other challenges include the increase of product and process complexity; variety of software vendors and their lack of support for the interfaces between systems; heavy load of changes to manage; communication to a growing configuration management community; and shorter product development lead time.

4.2. Configuration management in CERN

To achieve its mission of providing scientists from around the world with tools to study the building blocks of matter and origins of the universe, CERN builds and operates huge particle accelerators on the border between Switzerland and France, close to Geneva. It has approximately 2,350 staff, 2,000 contractors and 10,000 visiting scientists, with an annual budget of about 800 million EUR. As an integrated owner-operator, it has responsibility for the full asset life-cycle. Development and delivery of each particle accelerator is a major project. The Large Hadron Collider (LHC), for example, involved millions of high-tech components installed in a 27 km long circular tunnel, 100 meters below ground, with particles accelerated to 99.999999% of the speed of light, corresponding to over 11,000 revolutions per second. The design phase took approximately 20 years, and the work was globally distributed with collaborators in more than 80 countries across five continents. The material cost was approximately 3.7 billion EUR.

While a lot of the design work and drafting is sub-contracted, there are about 150 full time designers using CAD, who are engaged in designing in 2D and 3D, updating information, and upgrading designs on the different projects. A digital system for data management has been used since the late 1990s, with 5,700 active users registered on the system. The volume of data is significant: The whole complex involves 100 million components; with about 1.5 million documents and drawings; 1.6 million individually registered assets; and almost 2 million equipment interventions logged. The velocity of information involves about 3,000 new pieces of equipment a month, and 7,000 new documents and drawings created a month. In work on an accelerator in 2009 there were approximately 12,500 equipment interventions per month. This data is of significant variety, it includes physics parameters, technical specifications, layouts and equipment codes (in specification); simulations, bill of materials, documents and drawings, (in design); manufacturing processes and test procedures and results (in manufacturing); installation and safety procedures; and "as-installed" documentation (in installation); and radiation measurements, material composition, recycling procedures; and waste management (in dismantling).

There is substantial interest in configuration management within CERN with an ongoing initiative to update processes of change control. The manufacturing team has a mature understanding of configuration management, and uses the work breakdown structure to manage assets through the supply-chain, and follow up changes. Manufacturing software is linked to the digital system for data management, where manufacturing data on critical equipment can be entered. There is interest in improving this for the design data including production drawings; and a desire to formalize the feedback from operation and maintenance teams as input for new designs and standardizing of parts. Challenges include the:

- *Extended life-cycles* – Installations have lifecycles of more than 50 years, so they use historical data and formats, such as microfilm drawings, and collect missing information by scanning and photographing the system. New asset information will be relied on by operators in the mid-to-late 21st century, so needs to be self-explanatory and complete.
- *Large, complex and advanced installation* – Many pieces of equipment unique, designed specially, and the result of many years of research and development. New accelerators and experiments must be installed into the overall system of tunnels and facilities, for example a new accelerator reused the main part of an old tunnel, with some interventions such as ground construction work to upgrade it.
- *Support for a scientific culture* – The nature of the science means tolerances may be measured in microns (one micron is a thousandth of a milimetre) in an installation of several kilometers. Yet unlike the military context in which configuration management was developed, there is not a centralised command and control culture. The ethos is based around international research collaboration.
- *Major operational constraints* – There is no access to tunnels and equipment when scientific experiments are in progress. There is a long shut-down for maintenance work every 1–2 years, with a short technical stop every 1–2 months. Even then access is curtailed by the need to limit installers and maintainers exposure to radiation; and to cool-down and warm-up equipment after and before experiments.
- *Regulations for nuclear installations* – Installers and maintainers have to wait to enter certain zones because of the radiation generated. Radiation effects are calculated for each material. Where equipment or components are installed or removed, these have to be tracked. CERN is classified as a nuclear installation, so regulations are similar to a power plant, requiring traceable documentation of equipment, interventions and procedures.
- *Parallel design work* – Upgrades are managed by machine versions (2007, 2009, 2012, 2015 etc.) as different accelerator configurations are worked on in parallel. Changes include planned configuration changes across versions; and interventions to fix things. When equipment is installed, it needs to fit with what is there. Where there have been unexpected changes, installers have had to cut and weld equipment when installing it, modifying it on the spot to make it fit.

There is particular focus on managing such 'non-conformities', where changes happen to the design during the using, testing, installing or modifying the equipment. Such changes may result in a design not being exactly within the specification. How the equipment does not conform to specification is documented. Checks are made to establish whether equipment can be used, accepted as it is, or corrected, and how it might be corrected. Some equipment is bespoke and extremely expensive, so it may be accepted despite not conforming to specification if it can be adapted on site. 'As-built' information is required for maintenance and disposal, as well as the next generation design, so test data and new versions of the drawings need to be entered into the systems, along with the location of the installed equipment in the tunnel.

4.3. Configuration management in Crossrail

Crossrail acts as the delivery client for a new railway, which is due to begin operation in 2018. This £15.8 billion complex project aims to hand-over a physical and digital railway. It involves upgrading existing rail networks; building new stations; boring 42 km of new tunnels across central London from Paddington Station to Liverpool Street Station; installing, extending and commissioning a wide array of underground electrical and mechanical systems; and delivering the associated asset information to owners and operators. Contracts with the supply-chain require delivery of asset information as well as assets. There is a program of briefing the supply-chain on how to deliver this; and the quality of received information is benchmarked, initially every quarter, and now every 2 weeks. High quality asset information is required as the railway is expected to operate for over 100 years.

Configuration management is important in ensuring a consistent, validated set of asset information as a project deliverable. Through delivery there has been a small team focused on configuration management in a broader information management team. They are involved in developing processes for establishing and maintaining the integrity of configuration items in the preparation for hand-over. Digital system is used to manage data, where the project manages a significant volume of data, expecting to generate 2–3 million records in asset databases, 1 million model and drawing records; and quarter of a million GIS records. Asset information is stored within a repository, which is managed by data management software, with document, model and geographic information linked to this, but requiring different software to be viewed and edited. There is hence a significant variety of linked data in the form of asset information (and all the associated variables, such as author, approver, dates and versioning); digital *documents*, such as operational and maintenance manuals, plans, requirements, 2D designs; parametric building information *models*; and *geographic information*, such as asset locations.

Physical assets include rail-tracks, trains, shafts and buildings. The contractor is responsible for providing labels to identify assets as configuration items where practical, as well as equipment/serial number labels on all equipment, unless the size restricts application. The labelling of assets enables tracking of these items. Assets are also related to other assets to represent vital ‘powered by’ or ‘controlled by’ relationships. The associated information is controlled by contractors until they deliver ‘as-built’ information to Crossrail. From there onwards in the lifecycle, Crossrail locks down information associated with configuration items, equipment/serial number labels, and controls any further changes internally, to ensure the integrity of asset information in their digital system. The delivery client can introduce configuration items when design has matured, from detailed design onwards. Crossrail applies configuration control at the ‘as-built’ stage so changes to the configuration before handover are consistently maintained for the owner. There are currently around 155 thousand client configuration items, and by March 2016 the number is expected to rise over 600 thousand. Challenges include:

- *Rapid deployment in a temporary organization* – International standards for configuration and asset management were important, where obtaining the ‘buy-in’ to establish and maintain integrity is hugely challenging in the middle of a complex mega project.
- *Complexity and culture of delivery* – There are conflicts and interfaces among the many processes and procedures currently used in the industry for changes in programme baseline, design management, red-line (marked-up) and as-built drawings. There are challenges in understanding these and creating the culture that get managers and engineers to understand and use these existing change processes.
- *Multiple change processes* – the configuration management team has concluded that having multiple change processes, as is currently the case within the industry is not ideal, particularly where each change process may differ slightly and in some the same person is assessing the impact of change and making the decision of whether it should or shouldn’t be rejected.
- *Establishing a requirements-led orientation* – There is a need for a change from typical methods in the industry to mitigate the risk of scope creep, by having assets that conform to asset information, which in turn conform to requirements. The red-line procedure, for example, covers the process of annotating changes to drawings after they have been released for construction. The task, which is conducted by the site contractor, is intended to highlight approved, post-design changes from the original drawings, as reflected by an inspector of the built asset. The annotated drawings are then transferred to Crossrail. These records are used to later update the as-built drawings prior to data handover to the operator.
- *Determining operational requirements* – There are ongoing discussions with the future owners and operators regarding the type and format of asset information that will be used in operations; and a need to future-proof this information because of the long operational life.

An interface to the digital system has been reconfigured to facilitate this delivery of the large volume of asset-specific information. This specifies how asset information is to be identified, named, labelled, stored, synthesized and managed. Additional rules for numbering and naming complement the use of international configuration management standards to provide robust methods of maintaining asset information. By following a standard structure, and definitions, the aim is to organize asset information within the digital system and to hand it over to operators in ways that will be useful to future operation and maintenance. The interface helps users to transfer asset requirements to contractors, as well as capture the configuration items that those contractors return. Asset labels, equipment labels and serial numbers are used to represent configuration items, as defined in three different hierarchies based on location, function and classification. The system allows metadata searching; and provides the ability to explicitly link groups of assets to form a single system.

4.4. Approaches to managing change

While each organization, Airbus, CERN and Crossrail, operates in a different industry, similarities in their approaches and experience of using configuration management reveal shared characteristics and challenges of managing change in complex projects as asset information becomes a deliverable. Table 3 summarises and compares the relationship between

Table 3
Comparing how change is managed as asset information becomes a deliverable.

	AIRBUS	CERN	CROSSRAIL
Relationship between project delivery and operations			
Organization type	Service provider, with multiple customers.	Integrated owner-operator	Delivery client, handing over infrastructure provider(s).
Responsibility	Design, manufacturing, and servicing in operation.	Full life-cycle.	Design, construction and handover.
Information as a deliverable	For customer services to monitor operational aircraft.	For maintenance and upgrades to accelerators.	For station and railway operators and maintainers.
Responsibility for operation information	Final configuration of customer's aircraft; updating servicing information.	Asset tracking; work management information; disposal information.	Asset information at hand-over; not responsible for updating and maintaining.
Data aggregation and connections in project delivery			
Interfaces in digital systems	Between the development environment and the production environment.	Across machine version; and between manufactured and installed equipment.	Between the delivery client's design and as-built asset information.
Approach to managing change			
Configuration management	Used in the concept, product identification and definition stages.	Principles most familiar in manufacturing; initiatives to reduce non-conformities.	Used to manage and control as-built information; principles used in design.
Configuration items	Agreed by manufacturing and engineering through a 'congruency process.'	Different configurations of the machine managed in parallel.	Identified by the delivery client and labelled by contractors.
Complex product system – hierarchy and baselines	Functional baseline for requirements; engineering baseline for design; manufacturing baseline for production and installation; Customer service baseline for technical information.	Different generations of machines have baselines that are managed in parallel, making it important to get information about unplanned changes back into the design information.	Configuration items first identified at detailed design stage. Contractors manage the information up to an as-built baseline.

project delivery and operations; the data aggregation and connections in project delivery; and approach to managing change to provide asset information as a deliverable; and these topics are discussed in turn below.

In summary, each of these organizations is interested in configuration management in operations as well as delivery, though they vary in the extent to which they have lifecycle responsibilities. Because Airbus has service contracts it retains an interest in aspects of configuration management, such as conformity, throughout the lifecycle for aircraft that it has designed and manufactured. CERN is an integrated owner-operator, with responsibility for the whole lifecycle. As the delivery client, Crossrail hands over asset information for operation and maintenance. For each organization, the complex products – aircraft, particle accelerators and railways – have a long operational life (more than 20, 50 and 100 years) so information on assets, such as material, provenance, and design rationale, need to be available to enable efficient and safe operation.

Project delivery involves managing change in asset information as data-sets are aggregated and re-used through life. The volume, velocity and variety of data bring new challenges of version control, linkages across project stages and with other data-sets; and ways of structuring and organizing. While there is increasing integration between data-sets in project delivery, digital systems are not seamlessly integrated, but heterogeneous, with major transitions in the use of data through the project life. For example, in Airbus, there is a significant transition between the development and the production environment, in which there is manual work to restructure and re-link data (there may be instances where the product does not change, but connections between configuration items is different in engineering and production). All three organizations carefully manage the upload of information to their digital system because of the importance of its integrity. Where equipment providers have relevant asset information, these organizations will often duplicate that information in their own systems rather than link to it, because they need to ensure it will still be available in decades to come, when the manufacturer may have different equipment for sale and may not maintain legacy information.

Change is managed through the digital system, with configuration management software providing workflows for defining baselines for particular assets and asset systems; and for assigning roles and responsibilities for approving changes. This use of configuration management starts earlier in Airbus, than in Crossrail, where the use of configuration management is most pronounced in the control of as-built information. Each organization has a substantial and distributed supply-chain that has access to input relevant information, and to be involved in the approval of change within project digital systems. Design globally distributed in both Airbus, with 4 million parts supplied from 30 countries for A380, and CERN, with 80 countries across 5 continents involved in the LHC design. Crossrail has a substantial supply-chain of contractors involved in construction. Contractors within this supply chain have permissions to input 'as-built' asset information into Crossrail's digital systems, with information approved for purpose before it is made available.

Baselines are sometimes interpreted as an agreed description of the complex product system at a point in time. This study has clarified the types of baselines now used in Airbus, CERN and Crossrail increasingly focus on assets or groups of assets. This is most clearly articulated in Airbus, which uses functional, engineering, manufacturing and customer service baselines to manage related changes in relevant stages of the life-cycle. Thus there is no longer a simple baseline, but functional, product and other baselines managed on different timescales. Although in the 1950s configuration management enabled a move backwards to the baseline, in the era of big data this is not straight forward. Re-baselining may not account for different evolutions in data unless these are all linked; and there is significant work in industry to achieve this.

5. Discussion: renewed importance of configuration management in an era of 'big data'

For managers in these organizations that deliver complex projects, configuration management has become more, rather than less, important as we enter an era of 'big data'. New challenges arise as asset information has become a project deliverable; as data increases in volume, velocity and variety; and as it is aggregated and re-used; with connections (and potential connections) across internally and externally held data-sets. The organizations perceive a greater need for control through configuration management. The analyses suggest the need for integrity, in assets and in asset information, is a reason for this renewed emphasis on and interest in the associated control processes, as complex projects manage a significant volume and variety of asset information and hand this on to owners and operators. Ensuring integrity in operations is essential in industries that are regulated and safety-critical but organizational complexity, large distributed supply-chains and time-pressures increase the challenge of projects delivering the asset information to support this.

Configuration management has its origins in the mid-20th century. However, what is meant by configuration management has changed significantly. There has been a shift from relatively slow paper-based processes to faster database oriented practices; and extension of configuration management practices to cover the life-cycle through articulation of multiple baselines and aspects of the product. It is through such changes that configuration management has increased in importance as an approach to managing change in the delivery of complex projects, in an era of big data, rather than left behind with the paper-based processes of the late 20th century. There is some evidence that the speed of interaction with this data is growing, with for example Crossrail increasing the frequency with which it benchmarks its supply-chain from every three months to every two weeks. This is not just about doing change control better, but also about providing more visibility of quality of change control by different parts of the supply-chain. Such changes are within the paradigm of configuration management: they are beginning to be reflected in related standards and guides, with configuration management described as a component of the project management information system (PMBOK guide, 2013); and, during the timeframe of our study, the military developing and releasing a new interim standard (DOD, 2013), having considered the use of a 3D model, definition of as-designed, as-built and as-maintained baselines, and definition of the product (Windham, 2012). Thus change management is no longer a paper-based process, as implied by Fig. 1, but it is predominantly concerned with digital data. Digital workflows become important to manage the integration of information; and conformity between requirements, specifications and asset information.

As previous research has shown that users often don't follow the prescribed processes involved in configuration management (Ali and Kidd, 2014; Burgess et al., 2003; Kidd, 2001; Kidd and Burgess, 2010), there are opportunities to consider whether new digital technologies might enable other approaches to managing change. Airbus, CERN and Crossrail all face challenges in implementing control processes; and are actively engaged in developing new strategies. In complex projects, we anticipate limits to the extent to which 'big-data' will break the mould of established approaches to enable radically new, rapid and flexible form of organizing envisioned by Levitt (2011). However, we recognise the possibility of a broader shift away from baseline planning, as has occurred in software projects (Levitt, 2011); or a complete transition away from principles such as decomposition and hierarchy, as advocated by the military (Alberts and Hayes, 2003). Other approaches to managing change might be to mine data-sets to identify information relevant to the operational performance of assets; or to seek new scalable approaches to managing change in non-critical documents, where Wikipedia, might suggests a model in which changes are made, and then corrected; which contrasts with the more bureaucratic, pre-authorisation approach of configuration management.

While managing change is important to project management, configuration management has had limited attention in literatures on complex projects. Research on complex projects has instead discussed how systems integration capabilities are mobilised in innovation in construction (Gann and Salter, 2000); and in manufacturing settings such as aircraft engine control system (Brusoni et al., 2001) and flight simulation (Miller et al., 1995). This research on systems integration, like the work on configuration management, traces its history to the USA missile programme in the 1950s (Sapolski, 2003). Change management through 'configuration management' relates to systems integration, as it involves the decomposition of the complex product system to identify assets, and then manage change within these assets and their associated asset information.

6. Conclusions

While prior research has argued that digitally-enabled approaches break the mould of established approaches to project management, enabling rapid, flexible forms of project organizing; in this study we find Airbus, CERN and Crossrail, using relatively hierarchical, asynchronous, sequential processes to manage change. We conclude that the unstructured, uncontrolled nature of 'big data' presents challenges to complex projects that deliver assets. Thus this paper contributes by uncovering limits to flexibility where integrity is important. The potential to use 'big data' in these contexts presents a conundrum, similar to that discussed by Lagoze in science. While there is the potential for analytics to provide commercial advantage by revealing small patterns, ‘big data’ represents a paradigm shift that disrupts notions of integrity and force new ways of thinking and doing to re-establish it. It challenges the existing approaches to ensuring the integrity of assets in regulated and safety critical environments.

There are practical implications. The first is that as managers in complex projects begin to deliver asset information, as well as assets, they should expect changes in both assets and associated asset information, and plan to manage this change. The second is that managers should be aware of the challenges that an ‘era of big data’ presents to this process of managing change. Configuration management provides a set of tools for maintaining integrity in this context, and implementation of configuration management has changed and is changing as a result of digital technologies. As well as using these processes, there may be contexts in which there are opportunities for managers to seek new proactive approaches to using data from projects to understanding future scenarios. Managers seeking to benefit from ‘big data’, must do this while maintaining the validity of the information on which the delivery and maintenance of complex product systems rely.

There are also implications for research. This study returns attention to Morris’ interests in the history of project management; the centrality of change control to good project management; and the shift from project execution to broader questions of management of projects. There are a number of directions for further research. First, more needs to be done to understand the idea of a baseline. Morris critiques the ethos of important guidelines, such as the PMBOK Guide as to: “*plan and then put on cruise control*” (Morris, 2013: p. 282), where this misses the challenges at the front-end of projects; and the constant need for updating and modifying plans during project delivery. We need to understand more about the process of agreeing baselines; how baselines are used to managing changes in the configuration of assets, and how they are controlled across complex supply-chains. Second complex product systems may have different hierarchical descriptions and hence more needs to be done to understand how configuration items are identified. There are questions about when and how the complex product system becomes decomposed into assets that are then controlled, and also what information needs to be known about assets. Mapping different approaches might lead researchers to set out frameworks for understanding the kinds of change management that are most effective in different circumstances. Third, more needs to be understood about the process of ensuring the validity of asset information in digital systems that are constantly changing, where responses are required rapidly. Here, researchers might compare models, in which changes are made, and then corrected; with the more bureaucratic, pre-authorisation approach of configuration management. The broader visibility and interconnections between data-sets provided in an era of big data may alter the utility of different approaches.

Finally, there are theoretical connections to be made between the literatures. Our work has revealed particular disconnects between the literatures on configuration management and the strand of work on systems integration within the literature on complex projects. Further studies might explore their historical and contemporary interconnections between these, and situate concepts within broader literatures on modularity and product architectures that may be useful in understanding change. Such further research will continue to chart interconnections, described by Morris, between the evolution of project management and developments in systems engineering, modern management theory, and the evolution of the computer.

Conflict of interest

The university and authors have a strong research collaboration with Crossrail, which is indirectly and directly involved in other research, has funded consultancy and has connections through advisory boards. We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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