Systems integration in infrastructure projects: seven lessons from Crossrail

Article (Accepted Version)


This version is available from Sussex Research Online: http://sro.sussex.ac.uk/id/eprint/105727/

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher’s version. Please see the URL above for details on accessing the published version.

Copyright and reuse:
Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.
Systems Integration for Construction: Seven Lessons from Crossrail

Jennifer Whyte, BA (Hons) MA (Cambridge), PhD, FICE
Centre for Systems Engineering and Innovation, Department of Civil and Environmental Engineering, Imperial College London, London, UK
http://orcid.org/0000-0003-4640-2913

Andrew Davies, PhD
SPRU – Science Policy Research Unit, University of Sussex, Brighton, UK

Chris Sexton, BA (Hons) MA (Oxon) FInstRE FCQI

j.whyte@imperial.ac.uk

Draft updated 14/04/2021; Wordcount: 3161; Number of figures: 2

Abstract

Systems integration in construction has distinctive features. We propose a systems integration model for the delivery of complex infrastructure projects in which the client takes a leading role. We draw seven lessons for clients from Crossrail, to: 1) manage programme delivery as an integration activity; 2) actively manage systems integration; 3) ensure authority to make decisions; 4) maintain configuration control; 5) plan for a lengthy testing and commissioning phase; 6) appreciate supply chain products may be part of unaligned global R&D and development programmes; and 7) do final integration only when there is something to integrate. On extremely complex projects, the client needs to retain accountability though roles and responsibilities can be assigned to the client, delivery partner, supply chain, chief engineer and/or contracted systems integration firm. A key question for the client at the outset is thus how to distribute interface management and systems integration responsibilities while retaining oversight and accountability. Rather than managing through contracts, budgets and schedules, priority should be given to managing integration, with contracts, budgets and schedules that support and incentivise this integration.

Keywords
Project management, management, procurement

1. Introduction
There is renewed interest in systems integration in the construction of buildings and infrastructure, with the Institution of Civil Engineers (ICE) arguing for a need for engineers to shift mind-set to a systems approach (ICE, 2020). Systems integration is the set of activities that enables disciplines to bring engineered components together to deliver a whole system that is operable, maintainable and safe. While it is sometimes approached as a phase or a specialist engineering function, it also encompasses project-level technical processes, and program-wide strategic functions (Whyte and Davies, 2021). With a focus on process, the work of systems integration involves clarifying responsibilities, defining and validating interfaces, managing changes, and designing for manufacturing, assembly, and operations. We argue in this paper that the client needs to play a leading role in systems integration in major infrastructure projects.

Systems integration techniques have been developed in aerospace and defence (see also Hughes, 1998), yet systems integration in infrastructure delivery (Kouassi, 2015) may have distinctive characteristics. In many of the founding industries, the diverse disciplines work together over the many years that it takes, for example to develop a new military or civilian plane, there are mature systems integration processes. Conversely in the delivery of buildings and infrastructure, different disciplines engage at different stages of the project. Unfortunately, the focus in construction has become one of managing contracts rather than managing integrated delivery. Compared with the relatively closed systems in aerospace and defence, systems integration is concerned with relatively open systems with complexity across organizational boundaries. Recognizing the differences between construction and other complex product sectors, such as aerospace and defence, becomes important in meeting government ambitions in transforming construction, as represented by the UK Construction Playbook (HM Government, 2020), and implementing the robust processes, and understanding of roles and responsibilities envisioned by Hackitt (2018).

We propose a systems integration model for construction. This emphasizes the role of the client in organizing for integration at the start of extremely complex projects. While the client needs to retain accountability for systems integration, on such projects, a key strategic question they face is how to assign roles and responsibilities for systems integration at programme and technical
levels across the client, supply chain of designers and contractors, delivery partner, chief
engineer and/or contracted systems integration firm. The argument that systems integration
should take priority shifts attention from managing contracts, budgets and schedules to
managing delivery – the integration of deliverables into a working whole system – and it requires
changed incentives for contractors and project managers. We draw seven lessons from
Crossrail, arguing that the client should take an active role and retain accountability for systems
integration tasks at programme and technical levels. We develop this argument through the
following sections of the paper. The next section sets out our model of systems integration in
construction, characterising approaches to integration and introducing the Crossrail case. The
subsequent section then describes the seven lessons from Crossrail, and is followed by some
concluding remarks.

2. Articulating the model

Our starting point for articulating a model for systems integration in construction is the process
of project delivery. To start with the end in mind, systems integration requires attention to setting
projects up; evolution through the project; and the final stages of testing, commissioning, hand-
over and bringing in to use. These aspects are often captured in the classic ‘V’ diagram, used
by systems engineers to represent a project delivery process, from project start to project finish,
where delivery of an operating system is accomplished through work on the overall systems of
system, systems, sub-systems and components (shown in Figure 1). The advantage of this
representation over linear representations of the process is that it highlights the connections at
different levels between the downward stroke of the V involving processes of decomposition and
systems design of deliverables, and the upward stroke of the V involving processes of testing
the built deliverables.
Here the focus is on setting projects up, though elsewhere we have discussed the evolution (Whyte and Davies, 2021) and also the transition to operations (Whyte and Nussbaum, 2020). The work builds on a trajectory of recent work on systems integration, with the ICE report also highlighting the need for owners to own their projects and think of outcomes (ICE, 2020). This report also seeks to close the gap between sectors, future-proof projects, do shovel worthy not shovel ready projects, bake in systems thinking, encourage agile leadership and the use of data (ICE, 2020). Systems approaches are being use to emphasise the importance in developing human flourishing (CDBB, 2020), and to address grand challenges, such complexity and resilience and net zero pollution (Whyte et al. 2020). As remote working increases, Fraser and Rosser (2020) describe the importance of a Systems Engineering-based approach to design management to ensure clear roles and decision-making processes.

At the project outset, there are some strategic questions about systems architecture: What do you start by designing? The system as a system of products (which then need to be interfaced); or the systems as a system of interfaces (which the products are designed around). These lead to questions about ownership of sub-system delivery, and the interfaces between subsystem delivery. Before turning to the example of the Crossrail project, at the level of technical interfaces, we consider two basic integration approaches below.
2.1 Two Integration Approaches

Where two companies, work packages or contracts (with the latter sometimes being delivered by the same company) on a programme of work are required to integrate sub-systems, there are two basic approaches to bridging the interface, as shown in Figure 2. These are: a) the two companies doing the work on the subsystems can be asked to take responsibility for and manage the interface between them, reporting on their progress with arms-length governance and oversight; and b) a third party (either the client, a delivery partner or a separate firm) can be given responsibility for the interface and can sit in the middle on a day-to-day basis.

Figure 2: Approaches to integration

While it is normal to think of systems breakdown structures and work breakdown structures in terms of sub-systems and associated workpackages, we argue that there needs to be more attention to the interfaces. Hence on the integration of difficult sub-systems in large complex projects, there needs to be a lead interface owner, with specific responsibilities to integrate the sub-systems, as shown in model b. This interface owner can be the client, a delivery partner or a separate firm, but we argue that the client retains accountability and hence needs oversight of the process.

A particular challenge for the integration of sub-systems in construction is that the design of the different sub-systems may be at different levels of maturity and may also evolve over time. The
system breakdown involves decisions about where design can be rapidly progressed and
decisions made upfront, and where it is better to build in the flexibility because of uncertainties
such as rapidly evolving technologies (Gil and Tether, 2011). There is a culture of attention to
overall programme, procurement and commercials, with significant attention to contracts. What
we suggest contrasts with this, with attention first to the systems architecture, deliverables and
risk at interfaces, with procurement, commercials and contracts not seen as ends in themselves,
but providing incentives to support this focus on delivery of an integrated system.

To accomplish this, there is the challenge of first deciding on a systems architecture. Thus at
the project start (top left hand side of the V diagram in figure 1) there is a need to define what
the systems are, and to determine the procurement processes that support that. While cost,
time and quality need to be considered, the focus should be on the successful delivery and
transition into operation and use of the system of systems.

A challenge on every major programme of work is to get supply chain project managers to go
beyond the management of their contract, to take accountable for delivery beyond what is
explicitly specified in the contract. Procurement is an issue here, as margins are so frail in
construction, and it is challenging to build respect and trust in a competitive environment, even
in collaborative contracts there are no profit in doing more than is in the contract.

The breakdown of the systems architecture is not trivial on complex projects, where the timing
of the procurement strategies often excludes an approach that works with the supply chain to
develop the systems architecture. Work is packaged up and put out to open competition, with
the presumption that different contractors will work on different packages, whereas on major
projects it may be the case that the same contractor wins a number of different packages.
Hence it may be difficult to completely determine in advance where the most significant cross-
organizational interfaces will arise, and what the reporting structures should be.

While the owner and operator could be arms-length in a delivery project, focus on requirements,
change, funding and issues, we argue that they might want to get more involved in delivery.
One option to achieve model b) is that the client (either the long-term client or the delivery client)
can take a significant role in developing the systems and processes for the project. Where this involves planning by the central team, then the challenge is to develop a system that is both robust and not too complex to implement in the field, providing a suitable level of detail, but not taking too much effort. There is an optimum level of planning – not enough time, then things are not planned well enough, too much time and there may be too much detail making the processes difficult to implement as new people join the project and roles change. This is a particular challenge with systems integration, which could not be completed until the end of the process. It is for this reason that we suggest a third party (which could be a fat client) takes a day-to-day role in the middle of the key interfaces, engaged in the ongoing work of coordination, rather than focused solely on the deliverables.

**2.2 Crossrail example and differences with other industries**

There is significant organizational and technical complexity in the delivery of major infrastructure projects. On Crossrail, for example, Crossrail Ltd acted as the delivery client. Integration complexity was exacerbated by a situation where the end client for the train and the infrastructure were different (TfL and Crossrail Limited respectively). Yet as the same supplier companies won different contracts, they were sometimes working for different clients on different parts of the project, so for example Siemens was working for Crossrail on trackside systems, but on the train they worked on interfacing systems for TfL. As there was an overlap in the people involved, at the interfaces it was thus sometimes difficult to understand which particular activities related to which package. The infrastructure manager and future owner of five of the new Crossrail central London stations (London Underground) were different from the remaining stations and the routeway (Rail for London) and despite the fact that they both reported to TfL their assurance processes were different and they had separate engineering teams.

**3. Seven lessons from Crossrail**
With the client taking clear responsibility for systems integration for complex (systems of systems) projects, we have identified seven lessons for client teams from the Crossrail programme.

1. Manage programme delivery as the integration of a system of systems rather than a logically linked schedule of construction and testing activity.

2. Actively manage systems integration. Whatever is written in to supply chain contracts about managing interfaces it is the client who bears the integration risk and the client needs to manage the detail of systems integration at both programmatic and technical levels. The initial Crossrail strategy was to require the supply chain contractually to integrate systems with the client team measuring progress and stepping in as required. This approach was completely changed after the announcement of the delay in 2018 and from that point the Crossrail client team actively managed all technical integration activities.

3. Ensure authority to make decisions. The client system integrator must have the decision making authority (or at least access to the necessary governance bodies) to ensure the prioritisation of integration over schedule and cost in isolation. In practice this means making programme decisions based on integration requirements at the expense of schedule when delivery of a system of systems requires it.

4. Maintain configuration control throughout the life of the programme. In a 10 year programme leadership, technical staff and even document management systems will all change; configuration control must be unbroken from start to finish. The challenge is where to put effort into systems integration to reduce timescales and simplify processes. Information flow is critical here as documentation of design and design rationale needs to be complete enough that when people change over new decisions are not made without an understanding of the safety case, and the implications on the wider configuration. There was a significant programme of work to manage this configuration, and the associated organizational memory at Crossrail, as there is in projects in other sectors, such as CERN and Airbus (Whyte, et al. 2016). A safety case
might be written 10 to 15 years before it is needed, so written documentary evidence
needs to be well written and well organized to be useful in later decision-making.

5. Be prepared for a lengthy testing and commissioning phase. Too often, testing and
commissioning durations get squeezed by overruns in construction. The sheer volume
of testing and commissioning on digital programmes means that its duration is likely to
be very significantly longer than on traditional analogue programmes. As a benchmark,
testing and commissioning could take 30% of the total project duration.

6. Understand the extent to which supply chain products (such as trains and signalling
systems) are part of global R&D and development programmes which may not align
with your own programme. There is no such thing as a Commercial Off The Shelf
(COTS) product.

7. Final integration can only take place when there is something to integrate – supply
chain productivity and systems integration are inextricably linked. The delay to Crossrail
opening was not just systems integration. Neither the train, the rail systems in the
tunnels nor the stations were ready. There was greater complexity in the Supervisory
Control and Data Acquisition (SCADA) systems than anticipated.

4. Discussion and Conclusions
This work contributes by articulating a new model of systems integration in construction, in
which the client takes a leading role in systems integration in extremely complex (system of
systems) infrastructure projects. Here systems integration is given priority in delivery, and is
supported by rather than managed through contracts, budgets and schedules. In setting out the
roles and responsibilities across the project, is the underpinning principle that interfaces are
owned by a third party that is involved in the day-to-day work of integration. The client attention
is shifted from managing contracts, budgets and schedules to managing integration, and this
requires changed incentives for contractors and project managers.

The lessons from Crossrail are applicable to ongoing and planned complex infrastructure
projects in which the client is accountable for systems integration, and has implications more
widely for the delivery of infrastructure projects. The set-up of project deliver is crucial, and here
the model of systems integration may be differently implemented if there is a temporary or
permanent client. The client retains accountability for systems integration, but may differently
distribute roles and responsibilities according to the nature of the project, with Crossrail being
different, for example, to Heathrow T5, in which a permanent client was systems integrator; and
the London 2012 Olympics on which a temporary client and delivery partner were jointly
systems integrators.

The question of systems integration is of significant importance in the industry, especially in
relation to transforming construction, where offsite manufacture and assembly delivers tightly
coupled and complex systems and requires an early design fix.

Acknowledgements

The authors would like to acknowledge the Centre for Systems Engineering and Innovation at
the Imperial College London, the University of Sussex and Cambridge Autonomous Metro,
which collectively provided the time to support this project.

References

https://www.cdbb.cam.ac.uk/files/flourishing-systems_revised_200908.pdf


Fraser, N. and Rosser, R. (2020) Accelerating the Evolution of Design Management in
Construction: The COVID-19 effect, BuildOffsite.

Geraldi, J., & Davies, A. (2021) Transforming engineering systems: Learning from the dynamics
of megaproject organising. In A. Maier, J. Oehmen and P. Vermaas (Eds.), Handbook of
engineering systems design. Springer.

Gil, N., & Tether, B. S. (2011). Project risk management and design flexibility: Analysing a case
https://doi.org/10.1016/j.respol.2010.10.011


ICE (2020) *A Systems Approach to Infrastructure Delivery: A review of how systems thinking can be used to improve the delivery of complex infrastructure projects*, Institution of Civil Engineers, London, UK.


https://doi.org/10.1080/10286608.2020.1827396


**Figure captions**