



# The dynamics of systems integration: Balancing stability and change on London's Crossrail project

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## ABSTRACT

Systems integration is essential for the design and execution of large, complex projects, but relatively little is known about how this task develops over time during the life cycle of a project. This paper builds on the concept of “disciplined flexibility” to describe how systems integration can be conceived as a dynamic process of maintaining stability, while responding flexibly to changing conditions. We examine the dynamics of systems integration through a case-study of Crossrail, the construction of London's new urban railway system, which will be called the Elizabeth Line when it opens for service. The balancing act of stability and change manifests during critical periods of the project life cycle as various interdependent systems evolve with different degrees of maturity. We identify how various types of reciprocal interdependencies in complex projects such as Crossrail – at the system and system of systems levels – require ongoing monitoring and control, and the mutual adjustment of tasks.

## 1. Introduction

Early research established that systems integration is one of the core technical engineering tasks performed during the design and execution of large, complex projects in defence and aerospace industries (Hughes, 1998; Morris, 1994; Sapolsky, 1972; Sayles & Chandler, 1971). Innovation management scholars showed that systems integration has become a core capability of organisations responsible for coordinating large networks of suppliers involved in the design, production and integration of interdependent component parts of complex products and systems (Brusoni, 2005; Gholz et al., 2018; Hobday et al., 2005; Prencipe et al., 2003). This literature describes how systems integration has evolved from an early emphasis on the technical, operations task within systems engineering to its recognition as a strategic task in the business of managing projects (Gholz et al., 2018; Hobday et al., 2003).

Building on these important contributions, a stream of project management research has argued that systems integration is a key challenge to be mastered in the design and delivery of complex inter-organisational projects, particularly in infrastructure and the built environment (Davies & Mackenzie, 2014; Davies et al., 2009; Whyte &

Davies, 2021). This work has identified how strong capabilities in systems integration are required to cope with project complexity and uncertainty in interdependent and evolving systems (Davies & Mackenzie, 2014; Whyte & Davies, 2021), while achieving improvements in performance (Denicol et al., 2020). Despite a growing interest in the subject, extant research has not identified how systems integration evolves during the development of complex projects. To address this research gap, this paper seeks to answer the following research question: *How is systems integration managed as a process over time in a complex project comprised of many interdependent and evolving systems?* We carried out an in-depth case study of Crossrail, one of Europe's largest infrastructure projects, because systems integration is identified as one of the main reasons why Crossrail has been significantly over budget and delayed by several years (NAO, 2019). We build on the concept of “disciplined flexibility” (Sapolsky, 1972) and recent work on systems integration in projects (Davies & Mackenzie, 2014; Whyte & Davies, 2021) to suggest that systems integration can be conceptualised as a dynamic process of balancing stability and change, while responding flexibly to changing conditions in complex projects. Our study of Crossrail shows how the process of systems integration entails a difficult balancing act between

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maintaining the “stability” to freeze the design and execute reliable and routine tasks, whilst retaining the “flexibility” to anticipate, adapt and respond to unforeseen changes while the project is under way.

The paper is structured as follows. In our review of the systems integration literature in the next section, we suggest that the concept of “disciplined flexibility” is an important, but poorly understood research area that requires further conceptual development. In the following section we describe how our in-depth qualitative case study was designed to explore the question of how stability and change is managed in the case study of Crossrail. The findings section presents the case study, with analyses of the data collected, before proceeding to the discussion of the evolution of systems integration (as meta systems integration) across the systems of systems and systems integration levels. In the final section, we conclude by articulating the implications of disciplined flexibility for managing stability and change, drawing out recommendations for practitioners and areas for further research.

## 2. Systems integration – Theoretical background

To develop an understanding of the dynamics of systems integration, we build on recent research by Whyte and Davies (2021) that articulates the increasing importance of emergent complexity and uncertainty in systems integration, as it became used outside the closed world of US missile defence programmes in more open settings such as urban infrastructure projects.

Systems integration was created in the 1950s and 1960s to coordinate the design and integration of complex systems in the aerospace and defence industry and became a core element of the new discipline of systems engineering (Davies, 2017; Hughes, 1998; Johnson, 2003). A new type of specialised organisation – Ramo-Wooldridge – was established to oversee systems engineering and integration of the Atlas Ballistic missile programme (Hughes, 1998). Since then, complex projects have relied on a systems integrator to define the overall design for the system, its component parts, and interfaces between them, including coordinating the network of component and subsystem suppliers involved in phases of design, production, integration, commission and handover to operations (Brusoni et al., 2001; Hobday et al., 2005; Prencipe et al., 2003; Zerjav et al., 2018).

Yet, while early literature explored how systems integration was a new form of organisation and process for managing large system-based projects including the Polaris ballistic missile (Sapolsky, 1972) and Apollo moon landing (Sayles & Chandler, 1971) programmes, it was since the 1990s that scholars in the fields of project management and innovation studies began to recognise the importance of systems integration as a core capability in the management of large, technology projects (Hughes, 1998; Morris, 1994) and, complex products and systems (Brusoni et al., 2001; Davies & Mackenzie, 2014; Davies et al., 2009; Hobday et al., 2005; Prencipe et al., 2003). Building on this work, and to situate our study in the wider literature, below we consider the system-quality of projects, discuss complex projects and systems integration, and then expand on the systems integration process and the question it raises about disciplined flexibility.

### 2.1. The system-quality of projects

Research on systems integration depends on the idea that a project can be considered a system of interdependent component parts that have to be integrated to achieve an overall goal (Whyte & Davies, 2021). When a system is nearly decomposed – or “partitioned” – into smaller components and subsystems, interdependencies amongst subsystems can be identified and predicted, and unexpected conditions – or “emergent properties” – can be minimised as new information becomes available over time (Simon, 1962). Hirschman (1967) was amongst the first to recognise the “system-quality” of projects and the need for integration, describing: “the extent to which many interdependent components have to be fitted together and adjusted to each other for the

project as a whole to become available and to yield the output for which it was designed” (Hirschman, 1967: 43).

Simon’s (1947) concept of “bounded rationality” has been applied to system projects where decision making is constrained by the cognitive limitations of individuals and the information and time available to solve a problem. When organisations are unable to reach a rational decision by finding an optimal choice given the information available, problem solving is facilitated by selecting from a range of options such as trial-and-error or learning from experience over time. Klein and Meckling’s (1958) study of weapons systems distinguished between two contrasting approaches to system development projects (Brady et al., 2012). A rational approach assumes that information is available at the start of a project and it is sufficient to reach an optimal decision about the system configuration and its component parts from a range of alternatives. An adaptive approach recognises that the information available is insufficient to reach an optimal goal (due to the bounded rationality of decision-makers) and relies on the learning gained from trial-and-error experience as project evolves to guide decision making.

As the overall system matures, problem solving in complex projects follows a tree-like path as a particular branch is selected from a range of options (Brusoni, 2005). As shown in Fig. 1, emergent complexities and unexpected problems must be addressed as systems mature by adjusting interdependent tasks (Tell, 2003; Whyte & Davies, 2021). These interdependent tasks require mechanisms to coordinate and adjust components and interfaces between them.

Building on Thompson (1967), scholars have identified three mechanisms used to coordinate or integrate tasks in projects comprised of multiple interacting components (Baccarini, 1996; Kumar & van Dissel, 1996; Williams, 1999). Integration by standardisation utilises established, stable routines and processes to address *pooled* interdependencies, whereas integration by planning employs careful scheduling, monitoring and control to address *sequential* interdependencies. In fully decomposable system, tasks performed in one part of the system can be isolated and performed separately. In complex projects, however, tasks performed in one component frequently have to be modified to match tasks performed by others. This problem of reciprocal interdependency is addressed in complex projects via coordination (or integration) by *mutual adjustment*: gathering new information, working collaboratively, and adapting to emergent and unforeseen problems in real time (Davies & Mackenzie, 2014; Eriksson et al., 2019; Morris, 2013). Reciprocal interdependency often occurs in new product development or high-technology projects where design and production tasks are performed concurrently and have to be adjusted as new information (e.g. changing technological specifications, performance or customer requirements) becomes available.

Reciprocal interdependencies can be differentiated by whether the task goals are *compatible* or *contentious* (Levitt, 2015). In the case of reciprocal contentious interdependencies, the coordination mechanism of mutual adjustment requires escalation and conflict resolution as parties involved are in deadlock. The collaborative and cooperative effort required to address reciprocal interdependencies in complex projects (Tee et al., 2019) can be hampered by transactional arrangements and inadequate sharing of information (Eriksson et al., 2019). Interdependencies that are not adequately defined at the outset when the systems design is established then have to be addressed by an ongoing and dynamic process of mutual adjustment during later stages of the project life cycle. Fig. 2 shows how interdependencies alter over time through the project life cycle. The evolving interdependencies require continuous monitoring, with various integration mechanisms utilised to deal with interdependencies between systems.

### 2.2. Complex projects and systems integration

Informed by a systems perspective, projects are often distinguished according to the degree of system complexity based on the number of components, interdependencies amongst them, and structural

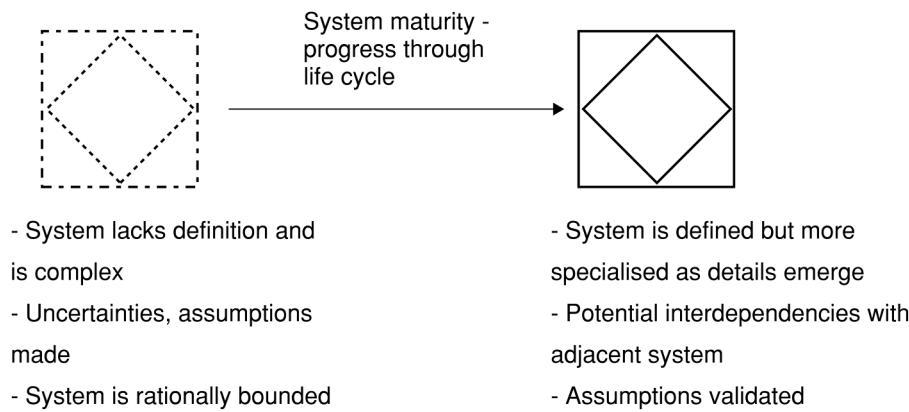


Fig. 1. System maturity (adapted from Tell, 2003).

arrangement in a system architecture (Hobday, 1998; Shenhar & Dvir, 2007). In Shenhar and Dvir's (2007) work, complexity is one dimension used to identify types of projects: component, system and system of systems (or array) projects. Gerardi et al. (2011) show that project complexity entails multiple dimensions, including dynamically changing and uncertain conditions. Brady and Davies (2014) address this by suggesting that in addition to the structural definition, dynamic complexity refers to the changing relationships amongst components within a system and between the system and its environment over time.

Complex projects, therefore, require systems integration to design, coordinate, fit together and adjust component parts into a whole system. While systems integration is often defined by practitioners as a specific stage towards the end of the project life cycle, most scholars agree that systems integration capabilities are required from design and production, to integration, testing and handover to operations (Davies, 2003; Davies et al., 2009; Erbil et al., 2013; Winch, 1998). There are also "two faces" of systems integration (Gholz et al., 2018; Hobday et al., 2005): in the first face, the systems integrator makes decisions about the design of the overall system architecture and interdependent component parts; and, in the second face, the systems integrator coordinates activities undertaken by a network of designers, component and subsystems suppliers.

Much of the extant research claims that systems integration applies only to "system" level projects to combine various components and subsystems performing multiple functions into a complete system or platform, such as an aircraft or weapon system. (Hobday, 1998; Hobday et al., 2005; Shenhar & Dvir, 2007; Gholz, 2003) recognised that systems integration is required for the most complex level of "system of systems" projects, comprised of a large array of interrelated systems and platforms, with each system performing independent activities organised to achieve a common overarching goal, such as constructing a national missile defence, airports and urban mass transit systems (Gholz, 2003). In complex interorganisational projects, the system of systems is decomposed into a hierarchy of levels, including systems, subsystems and component parts according to the degree of complexity. Such projects also vary in terms geographical configuration (linear railway vs clustered), interface boundaries, commercial contracts or incorporation of cyber technological systems.

In their study of the London Olympics 2012, Davies and Mackenzie (2014) introduced the concept of "meta systems integration" to describe the organisation and capabilities required to coordinate the integration of system of systems projects, comprised of the multitude of interfaces and multiple organisational boundaries. The meta systems integrator is the umbrella organisation that presides over and understands how the diverse collection of systems fit together into a system, while making trade-offs to reach the overall goal. It manages the sequential and concurrent development of systems, and coordinates interdependent tasks performed by a network of suppliers. While a complex project can be

structurally decomposed to its constituent systems with clearly defined and stable interfaces, the meta systems integrator has to address many unforeseen circumstances and changing conditions arising while a project is underway. An 'interface referee' can play an important role in reaching impartial decisions amongst conflicting parties and promoting the collaboration required to manage and define stable interfaces (Morris, 1979; Shenhar et al., 2016). An underexplored area of systems integration, to which we now turn attention, is the dynamics of the various organisations involved in integrating a system of systems and the influence on the stability of interfaces.

### 2.3. Systems integration process: balancing stability and change

The challenge of coordinating, fitting together and adjusting – or integrating – components of a system develops and changes over time (Brady & Davies, 2014; Sanderson, 2012). In his study of the Polaris program, Sapolsky (1972) recognised that "Whereas progress in each of the component subsystems could generally be anticipated, it was difficult to predict far in advance the moment of effective synchronisation for all of the subsystems" (Sapolsky, 1972: 250). Sapolsky introduced the concept of "disciplined flexibility" to identify how the "uncertainties of systems integration" are addressed in complex projects. Discipline is needed to keep certain options firmly fixed from the start (due to the physical constraints, interfaces and boundaries of the system) and provide the focus needed to meet schedules for project delivery. Flexibility is required to avoid a premature commitment to a specific goal by keeping certain options open to allow for new information to be collected and adjusted to changing requirements as a project evolves. This suggests that the system integrator must strike a balance between maintaining stability, while adjusting to changing conditions.

A systems integrator is faced with incomplete information about future conditions at the start and must be able to respond to new information that becomes available as the project develops over time (Sanderson, 2012). In a dynamic process, early decisions and assumptions are tested later when the system and its component parts are integrated (Prencipe, 2003). In complex system of systems projects, processes are established to ensure that a change in one system that might impair another one is rigorously evaluated and addressed (Brady & Davies, 2014). Some form of change control process to uncover and address problems that occur at the level of individual systems, or the system as a whole is required to maintain stability (Whyte et al., 2016). Managing dynamic complexity, where individual systems are in reciprocal interdependence, is constrained by the conflicting interests, motivations and priorities of the multiple parties involved (Gholz et al., 2018).

Scholars suggest that systems integration should be reconceptualised as a dynamic process to balance the need for stability, while retaining the flexibility to deal with emergent, changing and unforeseeable

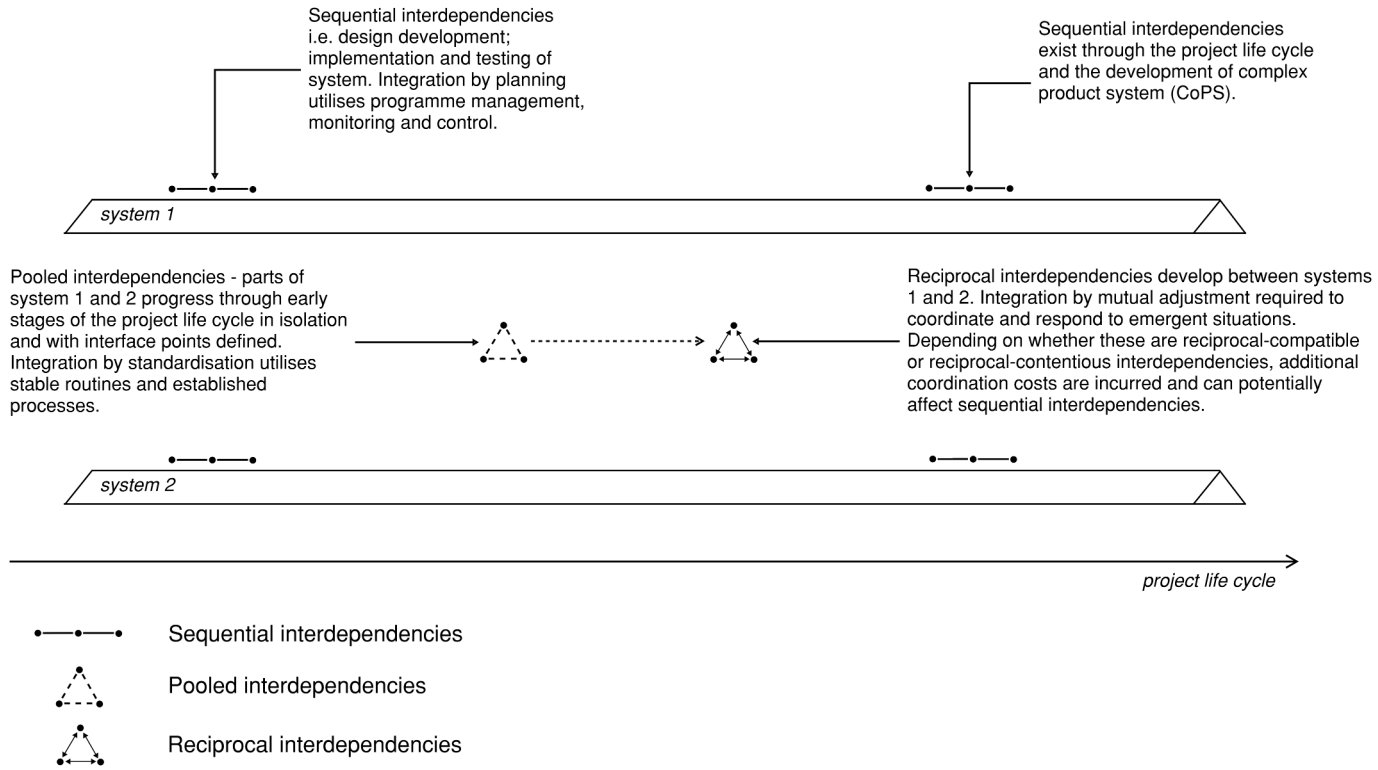


Fig. 2. Interdependencies over time - balancing stability and change

conditions during different phases of the project life cycle (Davies & Mackenzie, 2014; Whyte & Davies, 2021). Systems integration capabilities are required to coordinate known and stable components at a specific point in time (Sapolsky, 1972), and across several trajectories of uneven and dynamically changing developments. However, more research is required to understand how systems integration is performed in practice at a particular point in time and how it varies across the different levels – system and system of systems – within a project (Whyte & Davies, 2021). Furthermore, there is a need to understand how systems integration is one of the core processes or activities of a project delivery model (Davies et al., 2019) to ensure that components and systems are designed and integrated across organisational boundaries to achieve successful outcomes (Denicol et al., 2020; Whyte et al., 2016).

Building on this theoretical grounding, we now turn to the empirical

**Table 1**  
Secondary data sources and description.

Data source	Data source type	Publication date	Description
Institution of Civil Engineers (ICE)	Proceedings	September 2016	ICE proceedings outlining Crossrail project delivery and execution strategy. (Tucker, 2017)
Institution of Civil Engineers (ICE)	Proceedings	May 2017	ICE proceedings outlining Crossrail programme organisation and management. (Wright et al., 2017)
Public Accounts Committee (PAC)	Oral evidence	6 March 2019	Oral evidence by CRL leadership and board executives to the Public Accounts Committee (PAC) on Crossrail delay and delivery challenges. (PAC 01, 2019)
London Assembly	Report	April 2019	Examination of the circumstances behind the programme’s failure and implication of its delay by the Assembly’s Transport Committee. (London Assembly, 2019)
Public Accounts Committee (PAC)	Oral evidence	19 June 2019	Oral evidence by CRL leadership and board executives to the Public Accounts Committee (PAC) on Crossrail delay and delivery challenges. (PAC 02, 2019)
National Audit Office (NAO)	Report	3 May 2019	Report examines the causes of cost increases and delays to the Crossrail programme. (NAO, 2019)
Transport for London (TfL)	Project Independent Review	23 January 2019	Project independent review report by KPMG commissioned by the Joint Sponsor Team (DfT and TfL) on the governance, financial and commercial arrangements in Crossrail. (KPMG, 2019)
Transport for London (TfL)	Schedule Assurance Review	21 November 2018	Independent peer review of the Crossrail Schedule Assurance and Master Operator Handover Schedule (MOHS). (Boss, 2018)
Crossrail Learning Legacy	Project documents	20 May 2019	Technical Assurance, System Integration plan and Interface procedure detailing the arrangements adopted by CRL to deliver the Crossrail programme. (CLL, 2019)

study through which we addressed the following research question: *How is systems integration managed as a process over time in a complex project comprised of many interdependent and evolving systems?*

### 3. Research methods

A qualitative single case study approach (Goffin et al., 2019; Yin, 2003) is used to examine the dynamic process of systems integration and how challenges of balancing stability and change were addressed in a complex project. The rationale for choosing this research approach is that it addresses the research question and limitation identified in the literature (Alvesson & Sandberg, 2011), enabling an in-depth analysis of key phases within the project life cycle and its eventual integration to achieve a common goal. The research is based on the analysis of both secondary and primary data to build theory (Pettigrew, 1990).

#### 3.1. Case selection

Crossrail is a complex high-profile project which entails the delivery of a new urban railway called the Elizabeth Line running through the centre of London. The project requires significant capabilities to meet the organisational and technical challenges over its scheduled 10-year design and construction life cycle. While the client, Crossrail Ltd (CRL) is responsible for delivering the project, it currently faces a number of challenges, with perhaps the most significant one involving integrating the various highly interdependent systems and transitioning to operational handover. We carried out a retrospective study of the integration and operational handover phase of the project. It represents an extreme case of a complex system of systems type project and provides a context with a high degree of project complexity and challenges faced by the meta systems integrator during the delivery life cycle.

We selected Crossrail as the focus of our research study because it represented an “extreme case” (Flyvbjerg, 2006) of systems integration on the most complex type of project, revealing the immense challenges of integrating a large-scale, system of systems. The case also provided the opportunity to examine how stability and change is managed with established structure and processes, whilst being able to respond to emergent, changing conditions through the delivery life cycle. Our study of Crossrail examines how individual systems were integrated into the entire Crossrail “system of systems” project. Using an embedded case study form of analysis, we deepened our focus on the critical interdependencies between stations and tunnels and used process theorising to understand the evolving focus of systems integration. The dynamic interactions we observed between CRL and its network of suppliers demonstrate that systems integration capabilities are required to coordinate and mesh together a collection of highly interdependent component parts into a functioning whole system. All authors have spent significant time conducting research in the Crossrail project, and the focus for data collection on the dynamics of systems integration was

**Table 2**  
Primary data categorisation.

Category	Organisation description	Project involvement status during interview
DE01	Depot (DE)	Active
CPT01	CRL Systemwide Project Team (CPT)	Active
DE02	Depot (DE)	Active
OS01	Other Station (OS)	Active
CS01	Central Section Station (CS)	Not Active
CS02	Central Section Station (CS)	Not Active
CPT02	CRL Station Project Team (CPT)	Not Active
CPT03	CRL Systemwide Project Team (CPT)	Not Active
CS03	Central Section Station (CS)	Active
CPT04	CRL Tunnels Project Team (CPT)	Not Active



shaped through this extended engagement.

### 3.2. Data collection

The research benefited from access to an unusually large number of informative secondary sources because the performance of this highly visible construction project through the centre of London was under immense scrutiny from politicians, professional bodies and the media. Data was obtained from publicly available sources such as the Crossrail website, specifically the Crossrail Learning Legacy (CLL), a National Audit Office (NAO) report, and oral evidence by CRL’s leadership and board to the Public Accounts Committee (PAC). The NAO report, produced by an independent parliamentary body, examined the difficulties between CRL and the Joint Sponsor Team, consisting of the Department for Transport (DfT) and Transport for London (TfL), that were encountered during the delivery of the Crossrail programme. Early information on how CRL managed the structural complexity of the project and developed its procurement strategy was obtained from the Institution of Civil Engineers (ICE). Redacted publicly available data from TfL concerning Crossrail has also been used to supplement this research study consisting of project independent review reports and schedule assurance peer reviews. In particular, the Crossrail audit reports produced by KPMG on behalf of the Joint Sponsor Team, which focuses on CRL’s governance, financial and commercial arrangements form part of the data utilised for this research study. Due to the voluminous secondary data available, careful filtering was undertaken to explore key themes related to this research study. Table 1 contains an overview of the specific secondary data used in this research study and its corresponding description.

In addition to this rich source of secondary data, we conducted ten carefully chosen in-depth semi-structured interviews with senior practitioners to identify precisely how systems integration worked in practice. Our primary data collection addressed specific topics pertaining to systems integration at various sections of the delivery life cycle and were used to explore decision-making processes and the views and experiences of participants (Galletta and Cross, 2013). Interviewees were identified through the authors’ deep engagement with the field and selected as they had specific knowledge related to the dynamics of systems integration, with a focus on the critical interdependencies between stations and tunnels (which were identified to be significant in the secondary data). The interview questions were typically open ended, allowing participants to elaborate on specific information pertaining to the research topic. Depending on each participant’s background in the

project, interview questions were re-structured, and in some cases, certain themes were explored in detail based on participants’ specific experience within the delivery life cycle of the project.

All research participants agreed to have their interviews recorded and transcribed. Due to the current media scrutiny regarding Crossrail, all primary data collected was confidential and anonymised for the purposes of this research study. Each participant was provided with a research information document prior to the interview, which contained information regarding the research topic and data collection methodology. Interviews were often conducted in the participants’ organisation or a suitable setting, and lasted typically one hour except for one interview, where it was decided that a phone interview would be more appropriate. Table 2 shows the categorisation of primary data, organisation description and project involvement status.

Transcribed primary data was categorised and coded so that specific information regarding the participant, or the organisation involved in the study was not included in this paper (Miles et al., 2014). Data has been omitted from this research study where it was found that the information was too specific and can be traced back to the participants’ and their corresponding organisation.

### 3.3. Data analysis

The analysis followed an abductive approach combining insights from theory and emerging patterns from secondary and primary data over time (Langley, 1999). While the process of analysis continued through the data collection and writing stages, and early analyses informed later data collection, major tasks involved in this analysis included the coding of secondary and primary data, and using process theorising in the comparison and contrast between sources to reach theoretical saturation.

First, we examined and coded the secondary data to extract key themes on the structure, processes, and delivery of a system of systems during various periods of the delivery life cycle, and to identify any documented systems integration challenges. Through this process we identified the critical interdependencies in the delivery programme (stations and tunnels). This analysis was informed by our ongoing reading of the systems integration literature, which led to an initial focus on how to manage multiple levels of systems integration in a complex inter-organisational project and allows us to look for theoretical insights on balancing stability and change across multiple parties over times. This theoretical understanding informed our interview questions, which led us towards a discussion with senior practitioners to unpack the

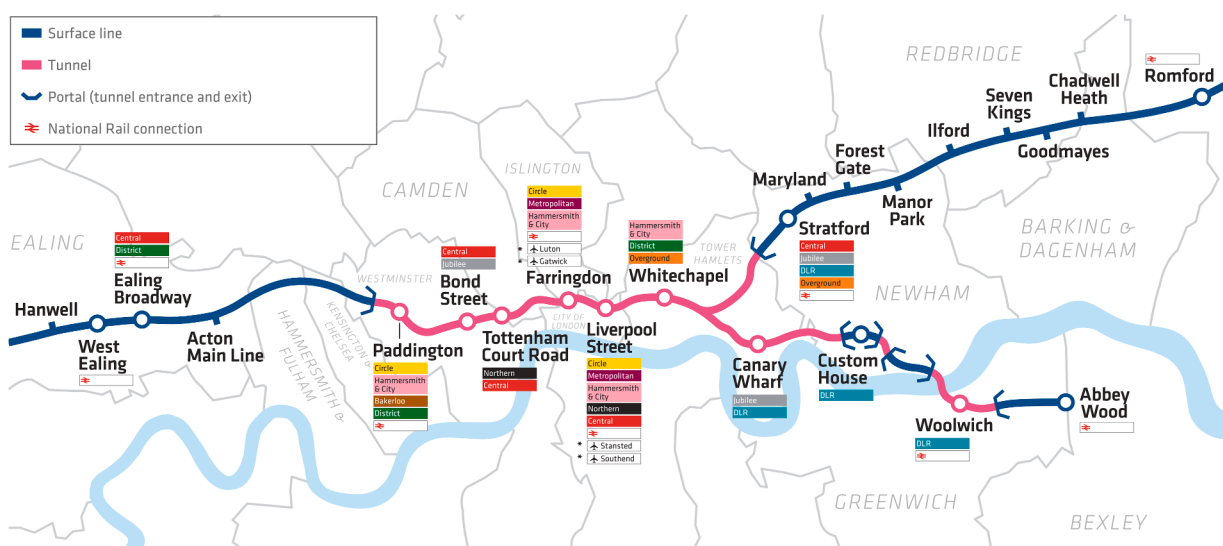


Fig. 3. Central section of Crossrail route map (adapted from Crossrail, 2019), which extends out to Shenfield, Abbey Wood, Reading and Heathrow.

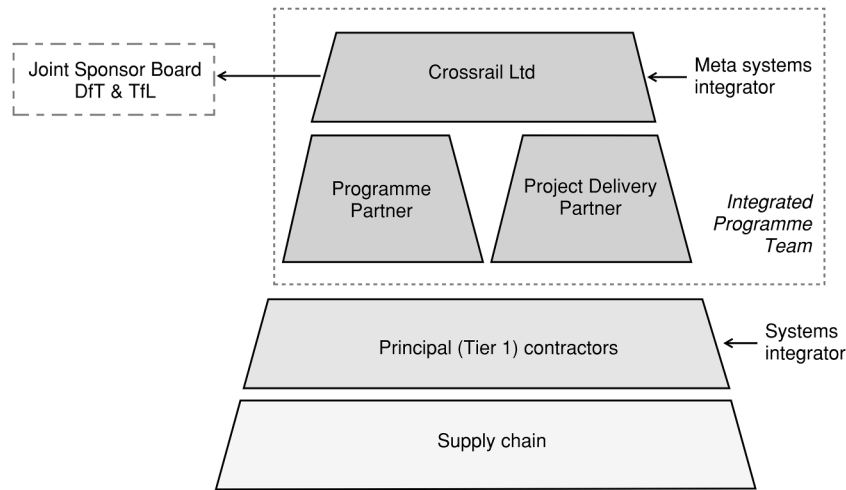


Fig. 4. Crossrail Integrated Programme Team structure.

different dimensions of change and stability.

Second, coding of the interview transcriptions enabled us to identify key themes emerging from the data (Miles et al., 2014). This coding was initially an open coding, done manually, to identify themes arising from the interviewees’ accounts (Glaser & Strauss, 2017). This step enabled us to develop a deeper understanding of the interview data, and the challenges of stability and change that this data revealed. Emerging themes from the interviews were compared and contrasted with the secondary data and the existing literature on systems integration, and discussed by the co-authors. The inductive analysis of the data through manual coding led us to identify a strong “voice from the data” about the balance and evolution of stability and change. This research gap was recognised by Davies and MacKenzie (2014) who called for more research to consider Sapolsky’s (1972) concept of disciplined flexibility and how this might provide novel insights to advance the contemporary debate on systems integration.

Third, we used data displays to tabulate our secondary and primary data, and used process theorising (Langley, 1999) to compare, contrast, triangulate, contextualise and synthesise the emerging findings from these different sources of data. We identified three phases in delivery and drew on the secondary and primary data to articulate the dynamics of systems integration within and across these phases. We interrogated the themes extracted from the dataset and their linkages to prior work on systems integration, complexity and interdependencies as well as the authors experience in the field and of the research literature on complex

interorganisational projects.

#### 4. Case study of a complex interorganisational project – Crossrail, London

This section presents our case study findings and analysis of the delivery of Crossrail. It begins with the characteristics of the project, the systems integration approach and CRL’s plan to open the Elizabeth line. This is then followed with the findings, which examines the evolution of the underground stations and tunnels from its early design development phase to the planned integration phase and CRL’s attempt at balancing stability and change throughout the project life cycle.

##### 4.1. Case context and characteristics

The Elizabeth line, which was known as Crossrail during its construction stages, is a new railway that has entered into service in 2022. It aims to provide an increase of 10% in passenger rail capacity utilising 24 trains per hour peak service with 200m long trains through central London connecting its western spurs, Reading and Heathrow to its eastern spurs, Shenfield and Abbie Wood (see Fig. 3).

CRL was established in 2008 as a dedicated temporary organisation and was given the mission “to deliver a world-class railway that will fast track the progress of London” by its joint sponsors DfT and TfL (Jones & Davies, 2016). The immense complexity of the Crossrail programme was

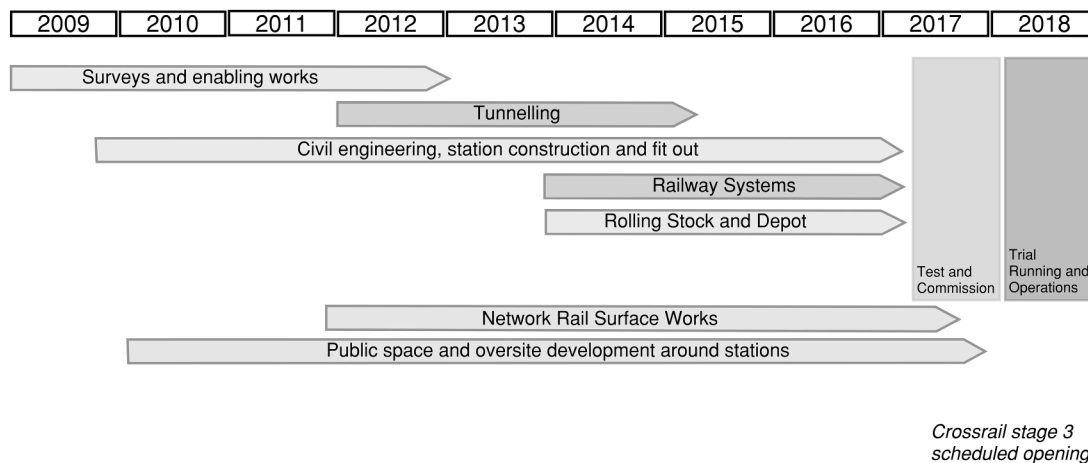


Fig. 5. High level schedule (adapted from Tucker, 2017 and NAO 2019).

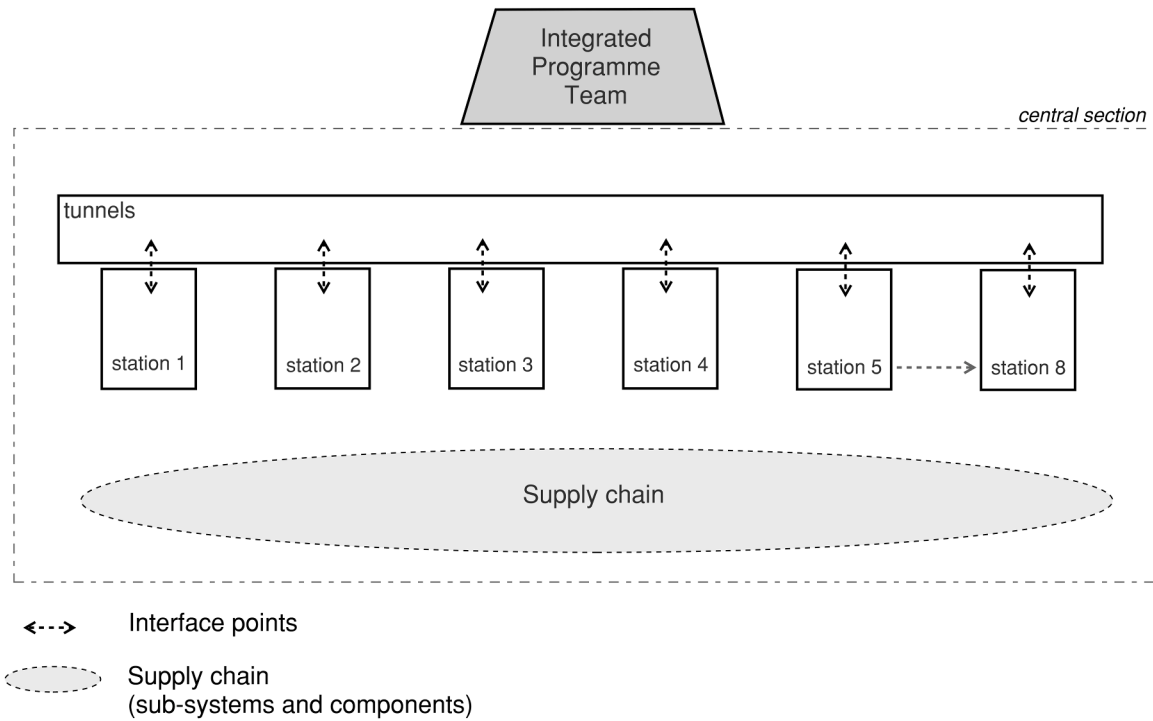


Fig. 6. Structural decomposition of central section – linear system of tunnels and underground stations.

acknowledged from the outset. CRL was assigned overall responsibility for systems integration and two organisations were brought in to provide CRL with complementary experience, knowledge and capabilities. The first was the programme partner consisting of a joint venture between CH2M Hill, AECOM and Nichols group. The second was the delivery partner for the central section, Bechtel, supported by Halcrow and Systra. Comprising of various engineering and programme management organisations, the programme partner and delivery partner worked with CRL to develop and establish the management structures and control processes (Wright et al., 2017). The meta systems integrator organisational structure evolved through the project delivery stages and due to perceived ineffectiveness of having separate entities delivering the project, the programme and delivery partner was combined into an

integrated programme team from 2011 onwards (NAO, 2019). The main objectives of the integrated programme team were to encourage collaboration between programme partner and delivery partner, and to bring in private sector expertise to the integrated programme team. Fig. 4 shows the organisational structure of the integrated programme team, where CRL functions as the meta systems integrator and remains accountable to its sponsors for the delivery of the project and ensuring that integration of the many interrelated systems meet the safety case as required by the regulator, the Office of Rail and Road (ORR). As partners to the integrated programme team, the programme and delivery partner were not contractually obliged to perform a systems integration role as part of their responsibilities (NAO, 2019; Wright et al., 2017).

The programme of works was divided to multiple sections as per the

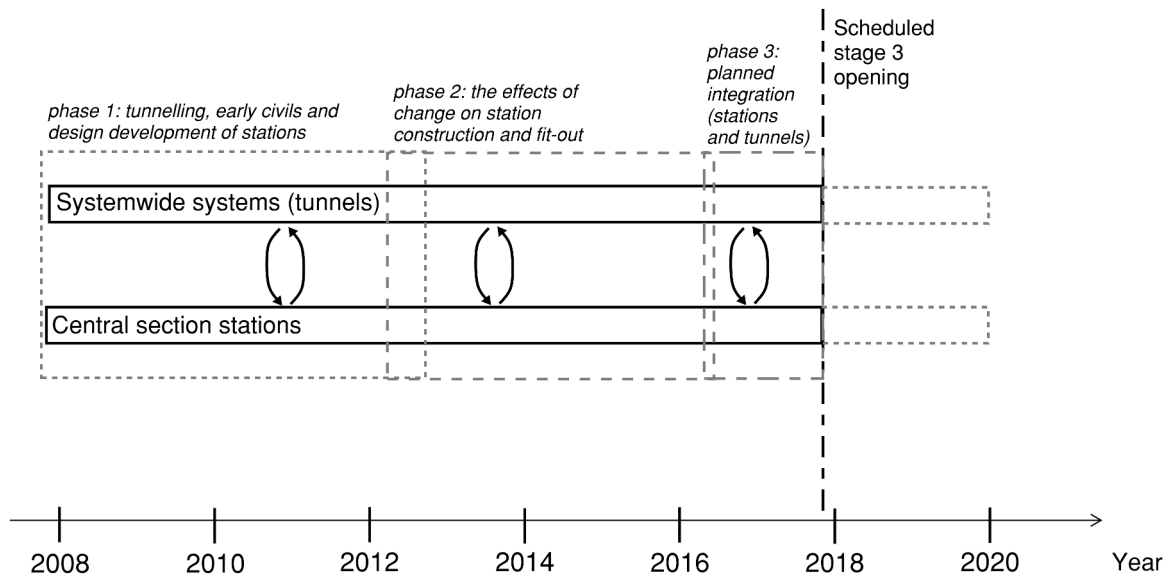


Fig. 7. System interdependencies and evolution through delivery life cycle.



**Table 3**  
Illustrated interview quotations and selected statements from audit reports, PAC interviews.

Period	Delivery phases	Secondary data (KPMG and NAO audit reports, PAC interviews)	Primary data (illustrated interview quotations)
2008 - 2013	Phase 1: tunneling, early civils and design development of stations	"The construction phase of the central tunnels has been well managed and on its own could be held up as an exemplar of a major project with public sector sponsors." (KPMG, 2019) The (design strategy) approach introduced the risk of conflicting designs between contractors and the potential for contractual change and delays while design work is resolved. Because CRL was responsible for integrating the overall programme, it bore much of the risk and impact of cost increases resulting from inconsistency of designs for different elements of the programme. (NAO, 2019)	"Programme is king...in all decisions made, it was always about keeping the Tunnel Boring Machines going" (CPT04 interview).  "CRL should have said earlier on that for 'X' system, all stations shall provide these structural openings...CRL wasn't making the decisions...the Tier 1 contractor at each station made their own local assumption, which was not always ratified centrally" (CPT02 interview).
2012 - 2017	Phase 2: the effects of change on station construction and fit-out	During 2015 and 2016, pressures on the programme began to show and continued to escalate through to the end of 2018. (NAO, 2019) Between 2015 and 2019, there was little pressure on key contractors to deliver the programme efficiently. (NAO, 2019)	"Cross-wiring of instructions to different gate impact reports ... required a lot of interfacing and to assess the design impact is so complex... to accurately assess the programme and commercial impact is almost impossible with the [New Engineering Contract] NEC contract" (CS02 Interview)
2016 - 2018	Phase 3: planned integration (stations and tunnels)	The build-up of compensation events on Crossrail are an indication of the high numbers of interfaces between contractors on the programme, and the prevalence of delays and change caused by poor integration of the work of multiple contractors. (NAO, 2019) Change is required in how the project is managed to focus more forensically on the 13% to go rather than reporting the 87% complete. (KPMG, 2019) CRL told sponsors that the handover schedule (MOHS) "...has always been ambitious and intended to drive behavior" and that "if all the Tier 1 contractors' programmes were simply added together the programme would end in 2020". (NAO, 2019) The absence of an integrated, realistic plan to sit alongside the ambitious handover schedule meant that CRL had a critical gap in the information available to manage risks to complete the programme efficiently and effectively. (NAO, 2019)	"It would be...the station interface managers and the systemwide interface manager would be coming into the conversation with their own interest at heart, not the overall project...there was no interface referee to assess risk and prioritise design implementation approach" (CS02 Interview) "You're almost going through an assurance process for bits of it rather than allowing the entire station to be built" (IPT01 Interview) "CRL reviewed the critical path, and they were in denial" (CS02 interview). "The Tier 1s just got squeezed more and more...and they started to introduce all these sectional requirements in order to facilitate their railway delivery programme" (CS03 Interview)  "...we would run at stuff...instead of taking a step back and questioning our approach because of the scheduled opening date. CRL should have been conscious of the time it takes to integrate changes into the design and taken a more pragmatic approach" (CS01 Interview)

following:

- Central section: The delivery of 42 km of tunnels complete with railway systems (electrification, non-traction power, signalling, tunnel ventilation, communications and control); 10 new stations in central London, each with 240m long platforms; and 8 shafts and portals. This includes upgrades to existing London Underground assets and delivery of two stations via private partnership;
- On Network Works: Upgrades to 31 Network Rail surface level stations on the existing network; and
- Rolling stock and depot: Separately awarded contract by Rail for London (RfL) for a new fleet of trains, each designed to carry 1500 passengers, and maintenance depots.

The programme of works described consist of large complex and interrelated sub-projects that have to be integrated by CRL to form an operational railway system, and this will need to be achieved via extensive engagement with various partner organisations such as Network Rail (NR), London Underground Limited (LUL), Rail for London (RfL), and Mass Transit Railway (MTR) as the train service operator. To achieve this within a 10-year delivery timeframe, CRL (Tucker, 2017) had to schedule the design and construction of concurrent work packages with overlapping phases, each with numerous interfaces, as shown in Fig. 5.

The scheduled opening date of the central section was delayed owing to the delays in the fit out of the central section tunnels and stations, and in the development of the onboard train software system. Informed by the traditional practitioner's assumption that systems integration is a task performed at a late stage in the project life cycle, three major integration tasks were identified: convergence of train software and signalling systems, station systems, and tunnel systems. These three

tasks are being completed in parallel with dynamic testing of the trains. Completion of these three tasks then transitions to the trial running and operations of the railway (Crossrail, 2020). These three major integration tasks are crucial to the next stage, Trial Running, and subsequently intensive operational testing after obtaining regulatory approval from Office of Rail and Road (Crossrail, 2020).

#### 4.2. Critical interdependencies in delivery programme – stations and tunnels

Our research addressed systems integration as an overall activity performed throughout the delivery life cycle of the Crossrail programme. As the overall meta systems integrator, CRL had to ensure that it had the necessary systems integration capabilities throughout its scheduled 10-year implementation life cycle. The delivery of the central section of the Crossrail route, which formed part of its stage 3 scheduled opening was a crucial aspect of its overall delivery programme. Numerous Tier 1 contractors were engaged by CRL and they functioned as the systems integrator for their respective work packages. Fig. 6 provides a diagrammatical view of the linear nature of the system of systems, its interdependencies and the system structure of the central section which consist of the tunnels and underground stations.

To further explore the systems integration risk factors, the critical interdependencies of two systems are examined as it evolves in phases from 2008 to 2018 (see Fig. 7). The integration of the *horizontal system* (tunnels) interacts at multiple interface points with the *vertical systems* consisting of the underground stations. The first phase was the framework design development of these interdependent systems with the design and the construction of the tunnels. The second phase was the effects of change on stations, and the emergent situations encountered by both CRL and the various systems integrators (i.e. Tier 1 contractors).

The third phase was the planned integration phase via the Master Operator Handover Schedule (MOHS), where key rooms were handed over to the systemwide Tier 1 contractors to speed up railway integration efforts, while large areas of the stations were still in construction.

Our findings from the audit reports concerning the delay of Crossrail and illustrated interview quotations are presented in Table 3. There are aspects within each delivery phase, where CRL attempted to maintain a crucial balance between stability and change using established structures and processes. The changing conditions encountered in phase 2 resulted from dynamic complexities that continued to evolve into phase 3.

#### 4.2.1. Phase 1 – Tunneling, early civils and design development of stations

The early stages of the Crossrail programme were dominated by the tunneling and early civil works for the stations. The complex engineering environment and constrained programme meant that the tunneling was the main priority, and hindrance to this programme would have far reaching consequences to the overall Crossrail programme. As noted by KPMG (2019), the tunneling, completed in 2015, was deemed a success in major project delivery and showcased the capabilities of CRL in managing and delivering a crucial milestone using established and robust programme management processes. Tight construction sequencing of the interfaces between the stations, platform tunnels and tunneling meant that certain stations had to progress their early civil engineering design to interface with the Tunnel Boring Machine key dates. This resulted in the civil engineering for the stations progressing ahead of the other Mechanical, Electrical and Public Health (MEP) subsystems. This is traditionally the case in a design process due to the priority of civil engineering design. However, a standardised and coordinated design strategy across the central section was not undertaken to safeguard space and services routes required for the MEP subsystems and future systemwide design.

There was a difference in design maturity in each station as the Tier 1 contractor made unverified assumptions on the interfaces between its subsystems within the station based on the information available and due to the lack of CRL oversight (CPT 02 Interview). Although CRL retained the responsibility for managing the design and ensuring that the integration of design components was undertaken across the defined interface points (Tucker, 2017), this was not comprehensively achieved prior to the subsequent station tender award. Therefore, this introduced a risk that was ultimately transferred to the Tier 1 contractor to manage and mitigate. This was further complicated by the design delivery strategy of CRL (NAO, 2019). Delays in maturity of the rail system design introduced further uncertainties to the early station design. As the design was developed further, new information was provided to the station Tier 1 contractors to implement.

Crucially, the defined interface points did not adequately address or foresee the reciprocal interdependencies that would be encountered between the station platforms and tunnels. The platform ends of each station presented a complex and conflicting environment:

*“every systemwide contractor wants their bit accommodated and is not interested in working together. It’s obvious that once you’ve set interfaces... that’s where your risks are...and it wasn’t made anyone’s responsibility and it didn’t get done...that’s a failure from the very top”* (CS03 Interview).

Potential conflicts that might arise from interfaces defined during the system decomposition were not foreseen, prioritised, or identified for resolution. Subsequently, changing relationships between the various systems over time were not accurately anticipated and potential interface problems were not visible in the monitoring and control processes.

#### 4.2.2. Phase 2 – The effects of change on station construction and fit-out

The delivery of Crossrail began to encounter difficulties in 2015 and 2016, with pressures on the programme continuing to increase through to the integration phase of the project (NAO, 2019). The joint sponsor team was notified about a significant safety issue when a transformer in Pudding Mill Lane failed in November 2017, resulting in an explosion

and subsequent delays to train testing. Initially reported as the primary cause of the delay in the overall programme by CRL (KPMG, 2019), this was subsequently re-framed in the following way: *“the main cause of delay was actually the lack of installation of the signalling systems, and the fact that the stations were a long way behind...”* (PAC 01, 2019, p.20). The central section stations, which are part of the critical path in the programme *“...started to slip around 2016 and into 2017”* (PAC 01, 2019, p.16) and the risks of testing the trains through an incomplete and functioning routeway was not adequately assessed by CRL as *“...you want the stations built before you put the train through the tunnel...”* (PAC 01, 2019, p.16).

The 36 main works contracts (NAO, 2019) for the central section were awarded using a New Engineering Contract 3 (NEC) Option C (target price contract with activity schedule) and CRL established dedicated project teams, who functioned as the authorised representative of the integrated programme team, to focus on railway systems, station construction and station fit out (Morris & Hands, 2017; Tucker, 2017). The appointment of Tier 1 contractors for the stations was undertaken in phases, with some stations starting construction a year later than others. The structural engineer was retained from the design development phase by CRL, whilst the architect, MEP engineer and specialist consultants were appointed by the Tier 1 contractor.

As the works information was progressed by the Tier 1 contractor, changes were introduced by CRL so that production of construction documentation met updated project requirements. These changes, which resulted from the maturity of systemwide design and changes to the station works information, started to increase in frequency and magnitude. While a change control process was in place, it was not fully utilised, preventing progress during the construction of the stations as more modifications were required to previously approved designs. Accordingly, the Tier 1 contractors issued notifications of compensation events as part of their contractual obligations. However, the NEC contract type was not able to respond to large numbers of changes, even with the proactive contract management that was specified in the contract:

*“NEC is a very good collaborative way of working...but it doesn’t work very well with significant amount of change because for each project manager’s instruction (PMI), a cost assessment and impact to programme is prepared...”* (CS02 Interview).

This is due to the administrative processes and formal communications within the form of construction contract, where an assessment of time and cost is submitted to CRL for each change instruction.

Subsequently, CRL negotiated supplementary agreements with all Tier 1 contractors. A large number of change instructions were included in multiple Gate Impact Reports, which provided impact assessment against documentation previously approved for construction via the stage gate process. This effectively, divided the construction of each

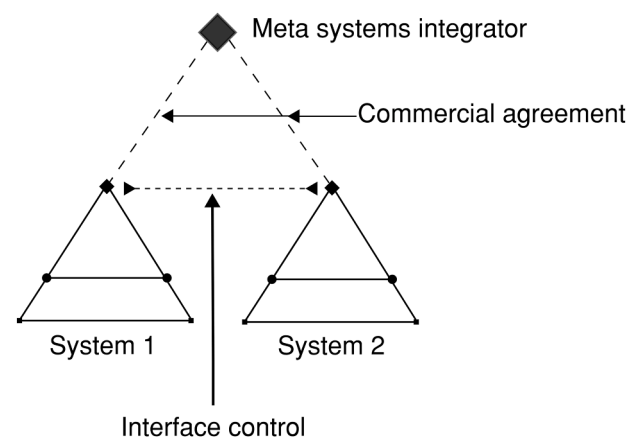


Fig. 8. System interdependencies – commercial agreement vs interface control.

station to smaller sections, with each consisting of many subsystems. As the station construction progressed, the Tier 1 contractor had to manage these individual packages of change instructions and obtain technical assurances from CRL to proceed. The volume, impact and pace of change resulted in the Tier 1 contractors adopting a varied approach to the implementation of stations. CRL's poor oversight, lack of scrutiny and ineffective use of change control process led to difficulties in managing the interfaces between the stations and tunnels. As the changes resulting from rail systems information impacted key areas within the station, the stability required for the station construction programme was hampered. The sheer volume of change required process workarounds, where the station Tier 1 contractor worked in an ad-hoc manner trying to solve the problem first, and then document it using the established processes to obtain CRL agreement. However, the Tier 1 contractor who was responsible for systems integration on the station project struggled to deal with multiple changes under severe time constraints. Changes progressed in one section of the station could potentially impact other areas awaiting design incorporation. This complex method of constructing a station and the subsequent integration of various subsystems required more effort and time. The lengthy technical assurance process took months for large Gate Impact Reports, increasing the coordination costs for systems that were dependant on each other as design implementation could not proceed.

Fig. 8 illustrates the need to address reciprocal interdependencies between two systems by mutually adjusting tasks. This was challenging because an interface referee representing the interests of the meta systems integrator was not actively present to establish stable interfaces between adjacent systems. In absence of a commercial agreement between interdependent systems, the meta systems integrator had to continuously monitor and control the interfaces throughout the delivery life cycle. However, in many instances, the control of interfaces and a thorough assessment of change impacting interdependent systems was inadequately scrutinised and required a more intense coordination effort. The lack of oversight at the individual systems integration level towards the interdependencies between adjacent systems impacted the critical path significantly. CRL were aware of the significant impact these changes were having on the completion of fit out in the tunnels and stations; however, there was little or no admission on the delays incurred: “CRL reviewed the critical path, and they were in denial” (CS02 interview).

#### 4.2.3. Phase 3 – The planned integration: stations and tunnels

As the construction programme moved towards the integration phase, CRL introduced the MOHS programme (Boss, 2018) to begin the integration of systemwide subsystems in the stations and to enable train testing, a crucial milestone for the Crossrail programme. The MOHS programme was poorly planned by CRL (NAO, 2019) and intended to “drive behavior” of the Tier 1 contractors. As noted by CS03: “it was very naive [...] this MOHS programme”. This effectively added another layer of complexity to the delivery of the stations and interdependencies with the tunnels, as approximately 90 programme critical rail systems rooms in each station had to be fitted out, tested, commissioned, and handed over by “key dates” to the relevant systemwide contractor. Each rail systems room had specific MEP requirements and was interconnected with various parts of the station, forming an intricate web that needed to be managed with the ongoing station construction and fit out programme. Agreements with all station Tier 1 contractors were not easily obtainable and by the time the MOHS programme key dates had been agreed, the overall programme had slipped. Faced with the new sectional requirements to facilitate train testing, the Tier 1 contractors were not able to respond to shifting conditions imposed by CRL. The complex interfaces introduced by the MOHS programme added a multi-faceted and layered complexity to the integration effort within the stations.

Transport of London (TfL), as the sponsor of CRL aspired to build a digital railway with the ability remotely control the station subsystems

from its control centre. Digitisation required significant supply chain capabilities to ensure that the central section stations were capable of remote monitoring and control. The uncertainties associated with integrating an extensive communications network, and functional testing of the numerous components at diverse geographic sites were also compounded by the late arrival of the MEP subsystems. The volume of work caused resource issues for CRL as the meta systems integrator, as it had to manage its supply chain diligently to ensure that specialist technicians are available across the central section stations to test and commission the various components (NAO, 2019). CRL stated that “[...] three things were coming together on those stations that had never been done before. One is that there were 10 of them; and the second is the aspiration...to produce a digital railway. Thirdly, not only was that going to be controlled locally in the station environment, but it was going to be controlled remotely, and I think that people had not appreciated and not understood the complexity of that.” (PAC 02, 2019, p.28). The challenge of integrating and handing over new railway stations with capabilities for remote control, while simultaneously meeting the scheduled opening date was not accurately reflected in scale, effort or volume of the planned work.

Consequently, the steadfast commitment by CRL to meet its scheduled opening date of December 2018 resulted in a lack of visibility of issues at the systems integration level: “[...] ruthless determination—to hit a particular date that was estimated 10 years ago. That created an environment in which people were very driven towards that date and not properly seeing all the risks [...] and poor reporting upwards of the realities on a day-to-day basis.” (PAC 01, 2019, p.4). There was an unrealistic appreciation of the systems integration risks having achieved initial successes in the tunneling and civil construction. Due to the poor availability of information, CRL had an inaccurate representation of some of the critical reciprocal interdependencies that were impacting the construction and fit out progress. There was little or no contingency or float to address these interdependencies and the dates agreed in the handover schedule were constantly under pressure (London Assembly, 2019). CRL needed to facilitate collaborative discussions to respond to rapidly changing conditions occurring at the systems integration level. To ensure that the scheduled opening date was met, CRL depended on adherence to stable processes to maintain the momentum required to meet the deadline.

Due to this desire to progress without adequate information, CRL became narrowly focused on meeting the opening date and lost sight of key issues, risks and pressures at the systems integration level. Since CRL paid insufficient attention to emerging systems integration issues, vital information and risks regarding the unfolding situation were not assessed and integration problems began to manifest throughout the deliver of the the central section station and tunnels. This was a notable feature during the later stages of the project. CRL was committed to maintaining what we call a “false sense of stability” as there was no effective overall systems integration with the holistic programme-wide perspective required to deal with the various risk factors and warning signs threatening to delay the opening of stage 3 train services. A more “realistic sense of stability” is crucial for meta systems integration level processes to work in the interests of the entire system of systems. However, such efforts were significantly hampered by the changing conditions encountered at the systems integration level. CRL was unable to strike a balance between the need for stability in parts of the project that needed to remain fixed, whilst responding and addressing new information as it became available.

To achieve its objectives, CRL had to integrate various systems, while allowing sufficient time to respond to unforeseen situations and changing conditions. Key to responding and adapting to these challenges requires the identification of interdependent systems that can be altered by the changing relationship with its surrounding environment. CRL's ability to foresee the compression of the programme and much needed awareness of emerging systems integration problems was severely hampered by inadequate systemic risk management, particularly where assumptions about systems interdependencies were not thoroughly vetted. With the high compounding risk factor of a compressed

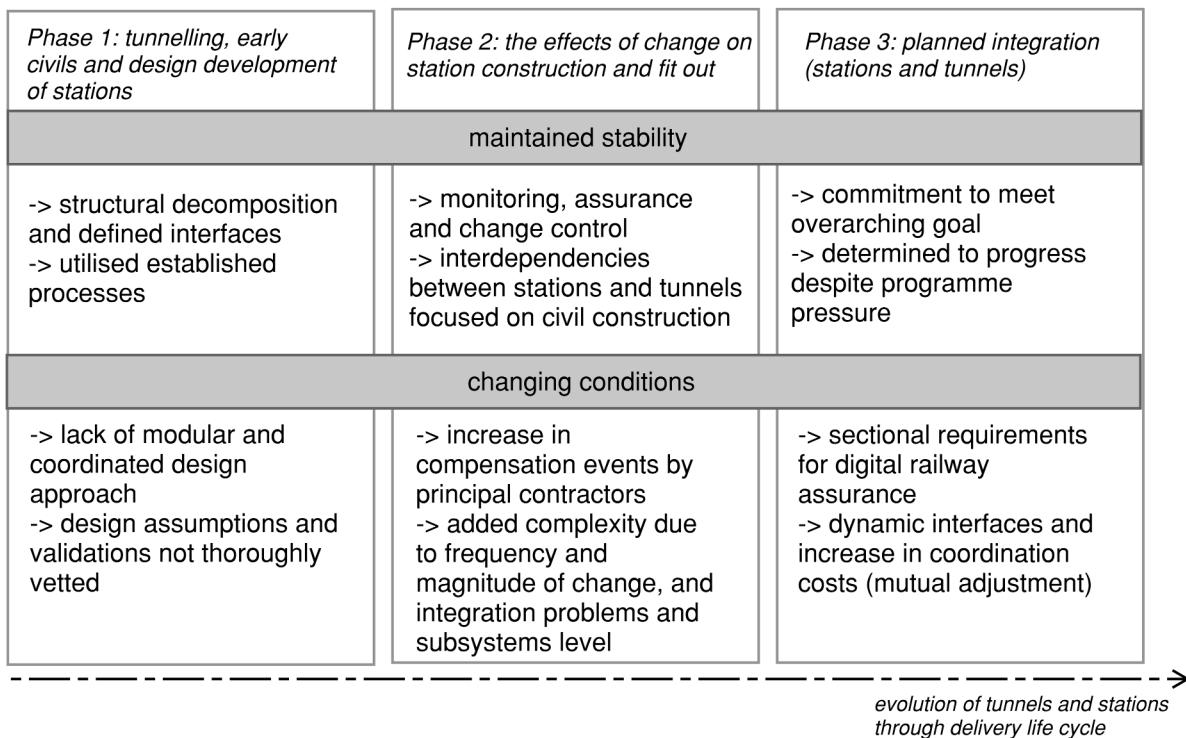


Fig. 9. Stability vs change – critical interdependencies: stations and tunnels.

programme, CRL had little time to assess and respond to these dynamic risks: “...the missing link has been the aggregation of adjacency of risks between the train, the tunnels and the stations. All these systems are...interrelated and dependant on each other” (PAC 01, 2019, p.6).

4.2.4. Synthesis of critical interdependencies in delivery programme

The findings from the critical interdependencies of three phases are synthesised in Fig. 9 to show the characteristics of how various elements were held stable and the changing conditions encountered through the phases of the central section, from the initial stages through to the scheduled opening date. It shows the effort made by CRL to balance stability and change through three phases of the construction of the stations and tunnels. The scheduled 10-year programme meant that numerous systems were developed concurrently, with different trajectories and shifting interdependencies. Throughout the different phases within the project, there were fixed points and changing conditions that were encountered by CRL. In some cases, these occurred simultaneously and continuously tilted between stability and change as the interactions between systems altered over time. The initial stability established with the focus on civils construction did not give adequate attention to the early standardisation required for the design development of the stations to safeguard the future rail and MEP subsystems. The emergent and changing conditions faced by CRL in phase two increased the pressure on the overall programme, where CRL attempted to maintain stability using established processes. However, this stability was exacerbated by the frequency and magnitude of change and compounded by a lack of robust change control processes coupled with identification of integration problems. The defined interfaces at the earlier stages of the project became more complex as sectional requirements was introduced to facilitate railway testing, effectively increasing the level of complexity at the systems integration level.

5. Discussion

Our case study of Crossrail was chosen to understand how systems integration is managed as a process over time in a complex project

comprised of interdependent systems. We showed how the systems integration can be conceived as a dynamic process which depends on structures, procedures and techniques to maintain stability, while being able to respond flexibly to changing conditions. The difficult balancing act of stability and change manifests during critical periods of the project life cycle as the various interdependent systems evolve with different degrees of maturity.

5.1. Meta systems integration

At the start of the project, the meta systems integrator was responsible for structurally decomposing the project to various constituent parts to match the complexity of the system of systems it was delivering. Breaking down the project into its component parts with the interfaces defined and identified helped to ensure that the systems were planned and delivered concurrently, to achieve the overall delivery schedule (Brady & Davies, 2014). The structural decomposition created a hierarchical architecture (Davies et al., 2011) with numerous systems integrators contracted to deliver various geographic sections of the project. Each systems integrator coordinated the diverse and specialised capabilities of the supply chain to produce its own system (Denicol, 2020), which had to be integrated into highly interdependent adjacent systems.

Despite facing incomplete information, evolving system maturity and uncertainties, the meta systems integrator was able to maintain stability by using a combination of established structures, processes and techniques to work within predictable constraints of the overall system. However, the meta systems integrator had to be sufficiently adaptive (Klein & Meckling, 1958; Sanderson, 2012) to manage the integration of systems with varying degrees of maturity (Tell, 2003) and address future conditions as new information became available. While development of systems can be performed in isolation for a limited duration, the changing relationships over time influences the interdependencies and trajectories of development between systems (Brusoni, 2005; Thompson, 1967). As the degree of interactions and corresponding complexity increase between subsystems and components (Gerald et al., 2011),



**Table 4**  
Conceptualising systems integration – balancing stability and change.

Period	Delivery phases	Extracted themes from case study	Conceptual Contributions
2008 - 2013	Phase 1: tunnels, early civils and design development of stations	Maintained stability for the construction of tunnels within the central section via established structure and processes, with primary focus on tunneling programme of works. Design consistency and standardization across stations were not coordinated centrally with the meta systems integrator resulting in varying levels of maturity within the design of the stations to cater for future systemwide designs. Assumptions made at the systems integration level remained unverified as the system development progressed.	Relative stability of assumptions (Williams, 1999) System maturity (Tell, 2003) Problem solving approach and inadequate definition of interdependencies (Simon, 1947; Simon, 1962; Brusoni, 2005) Decoupling of CoPS and trajectories of evolving systems (Brusoni, 2005; Davies et al., 2011)
2012 - 2017	Phase 2: the effects of change on station construction and fit-out	Multiple sub-programmes ran in parallel resulting in highly interdependent systems, where it was difficult to predict how systems will react to each other. The effect of changes from adjacent interconnected systems increased in frequency and magnitude. Subsequently, coordination costs from reciprocal interdependencies increased, and the corresponding effects of changing conditions posed a significant challenge to the meta systems integrator. Absence of stringent interface control between interdependent systems resulted in conflict at the systems integration level.	Structural decomposition of system architecture and interactions between interrelated systems over time (Brady & Davies, 2014; Denicol et al., 2020) Degree of interconnection between systems (Lawrence & Lorsch, 1967) Reciprocal interdependencies and mutual adjustment (Eriksson et al., 2019; Thompson, 1967) Systems integrator influence and motivations in interfaces (Gholz, 2003) Change control and stability of evolving systems (Johnson, 2003)
2016 - 2018	Phase 3: planned integration (stations and tunnels)	The interactions between interdependent systems in the critical path were exacerbated by dynamic complexities from requirements to meet railway testing, commissioning, and handover schedule. Uncertainties from the handover schedule while the stations were in an active construction stage meant that more pressure were added to the systems integrators and their supply chain. The meta systems integrator's capabilities were tested as it responded to emergent situations, and risks from integrating a highly interdependent system of systems became more evident. Critical gaps emerge in the meta system integrator's capabilities as it is unable to meet its obligation to deliver the project within its schedule timeframe.	Complexity and interconnectedness in system of systems (Shenhar & Dvir, 2007) Meta systems integrator capabilities within complex projects (Davies & Mackenzie, 2014) Maintaining stability with established structures and process while adapting to changing conditions (Davies & Mackenzie, 2014; Hobday et al., 2005; Principe et al., 2003)

systems integrators face difficulties in predicting how interdependent systems will react with future conditions impacting the relative stability of the systems. Uncertain future conditions require some parts of the system to remain fixed or frozen, while others stay open to solve problems that cannot be anticipated at the outset. The application of “disciplined flexibility” (Sapolsky, 1972) by the meta systems integrator as it presides over the system of systems was evident at the early stages of the project. However, this quickly unraveled through the crucial section of the delivery life cycle. Various systems matured unevenly with changing conditions unfreezing stable parts of the project, leaving the meta systems integrator with escalating coordination costs.

Informed by the systems integration literature, we argued that the meta systems integrator must respond dynamically to emergent and changing conditions, while maintaining stability towards certain parts of the system of systems (Sapolsky, 2003). The meta systems integrator faces the challenge of predicting future conditions that might disrupt stable systems and attempts to deal with new information arising from attempts to coordinate the integration of multiple interdependent systems. We identify how various types of reciprocal interdependencies – at the system and system of systems levels – in complex projects require ongoing monitoring and control, and the mutual adjustment of tasks. However, dealing with such interdependencies may increase coordination costs, impair project performance, and in some instances require conflict resolution (Denicol et al., 2020; Eriksson et al., 2019). We found certain reciprocal interdependencies that were initially compatible but became increasingly contentious as the project evolved. They were resolved by addressing deadlocks caused by commercial negotiations, scheduling complexity and escalating changes in scope.

The findings in Table 3 are summarised to extract key themes and this is presented in Table 4, where key aspects of the meta systems integrator's capabilities in balancing stability and change were examined and conceptualised.

## 5.2. Levels of systems integration

As our findings confirm that disciplined flexibility is required to manage systems integration: a dynamic approach to systems integration keeps certain parts of the system stable and fixed, while retaining flexibility for other parts to evolve through a separate trajectory. However, we go beyond Sapolsky's (1972) original observation by showing how this occurs at the two different levels in complex projects.

At the system of systems level, the meta systems integrator was committed to a carefully defined and fixed schedule to ensure that the certain critical elements, such as the tunneling, were not adversely impacted by unfolding situations. Defined interface points functioned as boundaries between adjacent systems, and these were effectively decoupled from the stable and time critical elements of the programme. Progress was dependant on predicting future conditions and ensuring that adequate provisions have been included in the system design to accommodate forthcoming information (Sanderson, 2012).

The absence of an ‘interface referee’ representing the interests of the meta systems integrator resulted in numerous unresolved conflicts as various systems integrators' attempted to influence the outcome of interface design decisions. While prior work has introduced the term ‘interface referee’ (Shenhar et al., 2016) and discussed unresolved conflicts (Gholz, 2003), our case significantly extends this discussion by showing how complex interdependent systems interact and evolve within the systems of systems. In some instances, mutual adjustments addressing reciprocal-contentious interdependencies at the interface between adjacent systems were not solved in the overall interest of the project (Tee et al., 2019). A consistent and standardised approach to coordinate the system of systems was absent in the design phase of the project, resulting in varying trajectories of development for certain technological sub-systems. The meta systems integrator made assumptions about future conditions and predicted potential impacts of these sub-systems. These assumptions were inadequately validated as the system of systems evolved through the delivery life cycle. As commercial agreements were finalised, significant risks were transferred and had to



be mitigated at the systems integration level.

Maintaining visibility of the dynamic interactions between highly interdependent complex systems was particularly important as the project moved towards the final phases of the project. Systems that were decoupled during earlier phases of the project to evolve through separate trajectories began to converge as these systems reached sufficient degree of maturity. Coordinating trajectories and integrating reciprocal interdependent systems as new information emerged required effective evaluation of potential conflicts to ensure that risks associated with unvalidated assumptions were addressed. The impact of change on adjacent systems increased in frequency and magnitude, forcing systems integrators to raise concerns about escalating costs and schedule overruns for the overall programme. Agreements to consolidate new information and implement the required changes were negotiated by the meta systems integrator. However, the stability afforded by this new agreement was temporary as new information continued to become available calling for subsequent adjustments and changes. For example, significant portions of the central section of the project such as the civil and structural construction of the stations had to be unlocked and adjusted to address reciprocal interdependencies amongst stations and tunnels.

As we saw in this case study on Crossrail, maintaining stability during sequential stages of the project was poorly coordinated at the meta systems and systems integration level. Attempts were made to unlock and re-open previously stable sections of the project, but considerable effort was required to resolve conflict and respond to new information as it became available. A cyclical process with dynamic interactions occurred when many interdependent systems were unlocked to respond to changing conditions as the programme moved slowly towards its scheduled completion. In its holistic view of various aspects within the programme, a lack of visibility persisted, and this subsequently impacted the meta systems integrator's ability to foresee risks and conflicts at the systems integration level.

## 6. Conclusion

By examining stability and change across complex interdependencies at the meta systems and systems level, this paper contributes to work on systems integration in projects. It builds on the concept of disciplined flexibility to describe how systems integration can be conceived as a dynamic process of balancing stability and change, which depends on structures, procedures and techniques to maintain stability, while being able to respond flexibly to changing conditions.

The balancing act of stability and change manifests during critical periods of the project life cycle as the various interdependent systems evolve with different degrees of maturity. We identify how various types of reciprocal interdependencies in complex projects such as Crossrail – at the system and system of systems levels – require ongoing monitoring and control, and the mutual adjustment of tasks. The empirical research shows how structural decomposition of the system of systems and identification of multiple parallel paths ensured critical aspects of the programme could be fixed and progressed to meet programme milestones. Defined interface points enabled the development of decoupled systems through separate trajectories. However, in the later stages of delivery, the project studied was poorly equipped to address an uncertain and changeable life cycle. Interface points had to be redefined to address the introduction of cyber technological systems and interdependent interactions on the systems integration level that were not adequately understood. These interdependencies typically transverse through multiple subsystems as a project evolves through the design, construction, testing, and handover phases. A false sense of stability prevailed in the project as it progressed to later phases of its delivery life cycle. A consequence of this was that the meta systems integrator, led by CRL, was unable to retain the flexibility to adapt, anticipate and respond to changing conditions as there was a lack of visibility at the systems integration level. As the complex interorganisational project moved

towards its integration and testing phase, the systems integrators faced the challenge of managing a poorly coordinated handover schedule resulting in severe delays, additional costs, and reputational damage. The changing conditions hampered the critical task of administering commercial agreements and increased overall coordination costs. The intricate combination of a commercial agreement and interface control in managing interdependent systems should be undertaken by organisations that are aligned and work in the interest of the whole system, rather than the interests of one particular organisation working on an isolated part of the project. However, the challenge of balancing stability and change may be exacerbated as various interdependent systems mature and are gradually meshed together as the project evolves through its life cycle.

The implication of these findings is that while practitioners need to pay attention to the ownership of interfaces in systems integration, they must establish how disciplined flexibility will be accomplished across project levels and during the life of the project. They need to consider where and when they can realistically achieve stability in the process of systems integration and retain flexibility to address unforeseen situations. Designs can be frozen with clearly defined interfaces when technologies are known and proven. But on many projects, practitioners also need to know when and where flexibility is required to ensure that the project can adapt to change. In this way, new technologies may be progressively incorporated while ensuring that the outcomes are not obsolete on completion of the project.

Our research study highlights how a client organisation, delivery partners and major contractors attempted to deliver a complex project, where multiple concurrent components and systems with reciprocal interdependencies were being integrated to form a fully operational system of systems. While this extreme case was chosen to reveal the difficulties organisations face when integrating a large-scale system of systems, we believe our findings may be applicable to many other complex projects where disciplined flexibility is required. We identify how various types of reciprocal interdependencies in complex projects such as Crossrail – at the system and system of systems levels – require ongoing monitoring and control, and the mutual adjustment of tasks. While focusing on a single case allows us to study the dynamics of systems integration in depth, we also recognise that the single case is a limitation of research.

This paper suggests some avenues for further research. There is the potential for further research to study how systems integration occurs on other projects and in other industries and systems, such as defence, smart motorways, and air traffic control. Given the practical interest and increasing industry focus on systems integration (DFT, 2019; ICE, 2020; Oakervee, 2020), researchers could study the dynamics where there are reciprocal interdependencies on projects that are implementing new processes and technologies. Undertaking this research will deepen our understanding of the dynamics of systems integration, the antecedents to systems integration problems, and the kind of leading indicators that would be useful to practitioners. Building on our theoretical contribution, researchers might also apply and test these concepts in different project contexts, including the subsystems level of a complex project, where the effects of change maybe isolated and locally managed, and across different functions and levels. Future research on systems integration can explore the role of the meta systems integrator in refereeing interfaces with complex interdependent systems as this is an important aspect of disciplined flexibility. There is also more research needed on nested activities within the systems integration level, which may also depend on the ability of organisations to adapt flexibly to changing conditions, while retaining the discipline required to move forwards towards a successful outcome.

Academics considering future research could connect the insights on balancing act of stability and change and evolution of system integration with recent debates in project management research to explore several new avenues. The dynamic relationship between the enterprise (meta-systems integrator) and project levels might inspire future research

regarding the specific capabilities (Davies & Brady, 2016; Leiringer & Zhang, 2021) to be built by different actors in the evolving megaproject organisational system (Denicol et al., 2021). The exploration of how to design such inter-organisational dynamics might lead researchers to reveal the connections between the systems integration (Whyte & Davies, 2021) and organisational design literatures (Aubry & Lavoie-Tremblay, 2018). Finally, researchers could consider new infrastructure delivery models (Davies et al., 2019; Whyte, 2019), analysing how procurement and commercial decisions might create the conditions to improve the systems integration process in complex projects. Across

these debates the concept of “disciplined flexibility” provides new insight into how systems integration can be conceived as a dynamic process of maintaining stability, while responding flexibly to changing conditions.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Acronyms

Acronym	Full name	Description
CLL	Crossrail Learning Legacy	Collection of good practise, lessons learnt and innovation from Crossrail delivery programme.
CRL	Crossrail Ltd	Organisation that was set up to deliver Crossrail that will become known as the Elizabeth Line.
DfT	Department for Transport	Government department responsible for the transport network in the UK.
ICE	Institute of Civil Engineers	Independent professional association of civil engineers in the UK.
MEP	Mechanical, Electrical and Public Health	Technical discipline field that encompass complex sub-systems and components for building services.
MOHS	Master Operator Handover Schedule	Schedule for key critical milestones for transition and handover.
MTR	Mass Transit Railway	Elizabeth line train operating company.
NAO	National Audit Office	UK's independent public spending watchdog.
NEC	New Engineering Contract 3	Form of construction contract.
NR	Network Rail	Owner and infrastructure manager of the Railway Network in Great Britain.
ORR	Office of Rail and Road	Government department responsible for economic and safety regulation of Britain's railways, and the economic monitoring of National Highways in Great Britain.
PAC	Public Accounts Committee	Responsible for examining value for money of Government projects, programmes and service delivery.
RfL	Rail for London	Infrastructure manager for the Elizabeth Line central operating section and will grant access to rail operators.
TfL	Transport for London	Government body responsible for the transport network in London.

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