TRANSPORT FOR LONDON

Department for Transport

APM
Association for Project Management

Crossrail Project 2019 to 2023:

Completing the Elizabeth Line

Crossrail LEARNING LEGACY

Because when projects succeed, society benefits

Contents

Foreword

Sue Kershaw, APM President

One of the many privileges of my role as President of the Association for Project Management (APM) is that I get to meet a diverse range of project professionals from all manner of different industries and backgrounds. Through my conversations with APM members and the wider project community over the past four years, it is clear to me that the project profession is at a major inflection point. Taken individually, developments like rapid digitisation, the drive to net zero and the breakneck pace of change would each represent a paradigm shift in itself. The project profession is trying to grapple with all three – and more – simultaneously.

The result is that we see major programmes, with Crossrail as a leading example, becoming ever more complex. At the same time, the stakes have never been higher. Successful projects and programmes are key to the UK's growth and prosperity as the country seeks to emerge from a challenging economic climate. Meanwhile, sustainability and the net-zero mission continue to pose existential questions that demand a rethink of how we deliver projects from the ground up.

Failure, therefore, is not an option. Yet project success rates continue to underwhelm. There are various statistics to compare, but past APM research has found that nearly 80% of projects fail to wholly meet their planned objectives. To meet the challenges we currently face as a profession, this simply has to improve.

This is where learning legacy comes in. Pioneered in the wake of the London 2012 Olympic Games, learning legacy has now become a widely adopted practice in major programmes, particularly in engineering and construction. The idea is to share knowledge and best-practice insights from these complex programmes to benefit those of the future, raising standards across the board and ensuring lessons learned are captured and implemented.

Having worked with the Olympic Delivery Authority back in 2012, APM is continuing to champion the benefits of learning legacies as official project management learning legacy partner for Crossrail, the programme to deliver the Elizabeth line.

The Elizabeth line high-frequency commuter rail link through London opened in 2022 to much fanfare. The state-of-the-art railway will cut journey times, boost London's transport capacity and provide an economic stimulus both in the capital and beyond.

Amid the positive headlines of 2022, it would be easy to forget that the delivery has been far from straightforward. To fully understand this, it's worth reflecting on just how much has changed since 2008, when the Crossrail Act received Royal Assent. Consider the radical pace of digitisation we have seen in projects and wider society in that time – and the growing complexity that increased interconnectivity brings. Then there's risk. If new risks emerge over the life cycle of a project that could scarcely be envisaged at its inception, they can play havoc with agreed budgets and timelines, especially when they are committed to very publicly – as in the case of Crossrail.

There is much to unpick, which is why Crossrail has established a learning legacy programme. The aim is to capture lessons learned across the programme's 15 years, which can then inform the planning of other major infrastructure projects in the UK and internationally.

This journal – a series of six papers – describes the lessons learned from the later stages of delivering the Elizabeth line and discusses the broader implications for leading complex major programmes. We hope you enjoy it.

Introduction

Andy Lord Commissioner, Transport for London

Dame Bernadette Kelly DCB Permanent Secretary, Department for Transport

On 24 May 2022 the Elizabeth line opened, serving new stations between Paddington and Abbey Wood, and subsequently connecting Reading and Heathrow with Shenfield and Abbey Wood. The new railway has performed above expectations since opening and this May will be brought up to the full peak service of 24 trains per hour, providing a valuable service to London and the south east that is already very popular among passengers. This will also mark the culmination of Crossrail, its many years of development, 13 years of construction and its lasting legacy to the UK.

The Elizabeth line will boost the UK economy by an expected £42bn. Through construction, Crossrail awarded 62% of its contracts to firms outside London, and created 55,000 new jobs and 1,000 apprenticeships, ensuring that the benefits of this major project, at one point the largest in Europe, were spread across the country.

Now that it is complete the Elizabeth line has rightly attracted praise across the world for its scale and ambition. It has set new standards for accessibility and design, introducing 10 brand-new stations to the network, and refurbishing over 30 existing stations, all of them fully accessible.

In the first eight months it has enabled over 100 million journeys, and every day 650,000 people choose the Elizabeth line as their preferred mode of transport – far exceeding the post-pandemic expectations of 500,000 daily users.

It is right that we share the lessons and experiences of the project with colleagues around the UK and across the world. The Crossrail Learning Legacy programme aims to do this by collating and sharing the learnings from delivering the Elizabeth line. This journal, and the corresponding event, are our opportunity to share the experiences of the latter phases of the Crossrail programme and the opening of the Elizabeth line.

The team began work in 2015, and since then over 700 items have been published, ranging from key processes and procedures, through to technical papers written by those working to deliver the project, and peer-reviewed papers by senior members of the team, such as those in this publication.

This journal hears directly from the key individuals who worked on Crossrail and focuses on the approaches they took on the programme and its leadership, integration, sponsorship, cost control and final operation.

The events of 2018 and the reasons for Crossrail missing the original opening date and being unable to deliver within budget are the subject of several reports including by national and London agencies. While some of the lessons included in those reports are also reflected here, the focus of the papers in this final Crossrail Learning Legacy journal is the work that was done between 2019 and 2022.

We'd like to thank everyone who has contributed to this journal, and to those past and present who have helped deliver the Elizabeth line.

We hope that this journal can help embed important lessons, experiences and recommendations in a way that will help colleagues to ensure the successful delivery of major infrastructure projects in the UK and around the world.

Project leadership: Getting Crossrail back on track

Background

In 2018 it was announced that the Crossrail programme could not be delivered to the original timescale and budget. The project sponsors made changes to the Board and Executive in response. This paper describes the leadership lessons learned in resetting the project in 2019–2020 and discusses the broader implications for leading complex major programmes.

1 Introduction

Author:

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Crossrail is an east-west combined metro/suburban rail system running under London, linking Reading in the west with Shenfield in the east. It runs for more than 100km, including 42km of new tunnels beneath London. After many years of planning and approvals, project implementation began in 2009. The project is now approaching completion, passenger services on the Central Section began on 24 May 2022 and the full service will be introduced by May 2023.

Crossrail is recognised as one of the most complex infrastructure projects in Europe, and for many years represented the gold standard in terms of transport project implementation. The complex civil engineering task of creating 42km of tunnel and 20 new underground structures, beneath one of the oldest and most populated cities in the world, has been widely and justly celebrated as an extraordinary feat of engineering.

However, not everything progressed entirely according to plan. The Central Section, almost entirely underground between Paddington and Abbey Wood, was scheduled to open in December 2018. In August 2018, just four months before the long-planned opening date, it was announced that the opening would be delayed – this came as a real shock to all stakeholders. The unexpected announcement at such a late stage created a total breakdown in confidence and trust between the project organisation and the sponsors and stakeholders. It also created a major hiatus in the progress of the project, as leadership and governance changes were made, and new plans developed to complete the railway. This paper captures some of the leadership lessons learned in the process of resetting the project and putting it 'back on track'.

2 The challenge of leading Crossrail

The aspiration to create an east-west railway corridor across London was first mooted in the first half of the 19th century, as a means of connecting the canals of the Paddington basin to the docks in the Thames Estuary in the east. In modern times, the programme that we recognise as Crossrail today first appeared on the proposed rail map in 1974. After several false starts, serious planning for the current programme commenced in 2001, a Bill was introduced in 2005 and Royal Assent was achieved in 2008.

Creating this new underground railway was always going to be an ambitious and uncertain endeavour. There are several reasons for this.

- The great majority of the proposed alignment was beneath London at a depth of 25–40m. London is one of the most difficult cities in the world to achieve this tunnelling drive, with 2,000 years of archaeological history, crossing the River Thames, large multistorey buildings with deep foundations and of course navigating a labyrinthine existing deep tube system.
- The construction of 20 huge vertical structures, nine storeys deep in the ground in a congested, busy megacity.
- The aspiration for an entirely digital railway, set at a time when the technology was immature or did not exist at all.
- The world's most complex railway signalling system, with a high degree of required research and development.
- Significant and extensive connection and interface with the existing classic networks of Network Rail and London Underground.

For these reasons, the construction of Crossrail, and its ultimate integration into a high-capacity railway for 250 million customers per year, was always going to be a very difficult leadership challenge.

This paper focuses on the lessons from Crossrail's challenges and is written in the spirit of helping and aiding future leadership of megaprogrammes like this one. In doing so, it's natural to focus on what went wrong. This is not to take away from or deny any of the huge and remarkable achievements of the leadership teams throughout the long history of the Crossrail programme.

3 The leadership route to unreality

Throughout the construction period, from the very start of construction in 2009 to the declaration in mid-2018 that the opening of the line at the end of that year would not be possible, the Crossrail programme was seen by all as a well-run programme; one that was 'on time and on budget'. The failure of the programme in 2018 came as a significant shock and surprise to those on the outside of the programme.

In reality, the programme had been under increasing time pressure from the time of completion of the tunnel drives, which had largely been completed successfully, overcoming many significant challenges.

However, slippage of the major civil engineering work, together with a total commitment to retain the Central Section opening date of December 2018, led to increasing compression of the all-important work of integrating, testing and assuring millions of individual components into an integrated whole – creating a functioning railway. While Crossrail had the theoretical system architecture in place to deliver the final product, there was insufficient understanding of the effort required to knit the whole system together, and therefore no real understanding of how long it would take – and how much it would cost. In fact, it took the new leadership team much of 2019 to build a complete understanding of everything that was required.

At the time of the programme declaring that the December 2018 opening date could not be met, the publicly declared completion status was 95%. Taking into account a realistic assessment of the remaining systems integration effort and the related risk, and a realistic assessment of how ready the completed elements were for that integration, that percentage should have been a great deal lower.

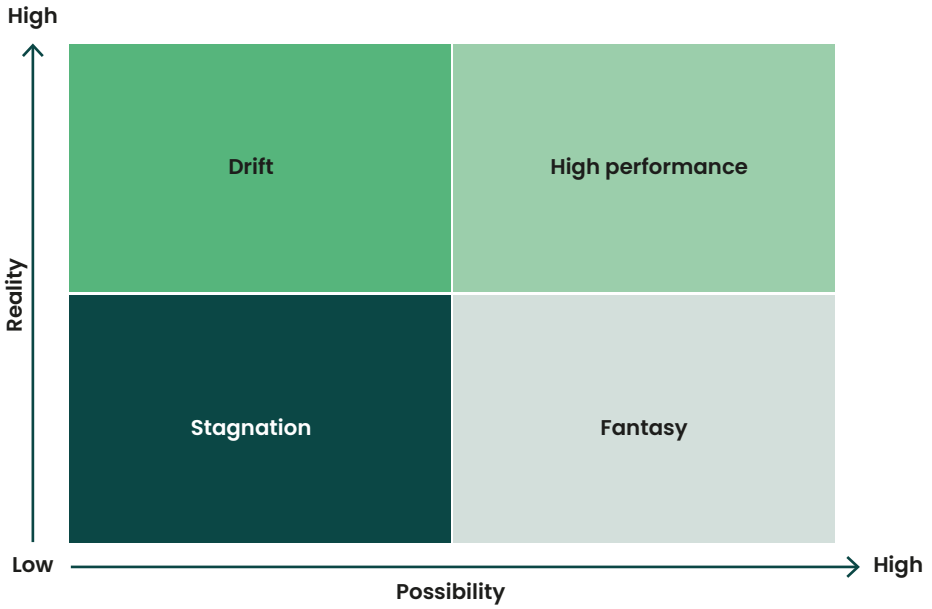

Figure 1 A performance model for complex programmes

"The reasons for this catastrophic loss of situational awareness and reality were complex and multifaceted."

Between 2013 and 2018, the programme gradually lost sight of the effort that would be needed to complete the physical works and bring the integrated railway into use. The bold aspiration/ambition of opening the railway on 9 December 2018 remained the same, but clarity on the level of completeness reduced over time. The reasons for this catastrophic loss of situational awareness and reality were complex and multifaceted.

It's hard to understate the extent to which the deadline of 9 December 2018 started to distort behaviour in the project as the date approached. Slippage in civils was occurring throughout the project; the programme was rescheduled annually, but the end date never shifted. This led to massive compression of the complex integration and testing phases. A culture that had created success in the early days also led to blindness in the later stages – a can-do attitude disconnected from reality.

The information reaching the top became disconnected from the reality at the workface, with people telling management what they wanted to hear. This reinforced a confirmation bias that became pervasive.

Crossrail had become too autonomous. Continuous schedule revision obscured slippage of internal milestones. The schedule was updated annually, so was always 'on schedule'. Absolute commitment to an immovable end date and the can-do spirit of the project team led to poor visibility of project performance at board level.

There is no doubt that the leadership thought Crossrail overcame many, many complex challenges. The tremendous early success in particular and great publicity surrounding it seems to have created something 'untouchable', and possibly led to the lack of deep independent assurance of work in later years, which, with hindsight, was obvious.

The focus on an immovable singular end date seems to have created the conditions for reality to have been lost collectively from the Leadership team, the Board, the sponsors and, crucially, the scrutiny of the myriad assurance levels.

In one perspective of leadership, before 2019 it could be said that the glory and most of the pain on the programme happened as a product of localised vision.

- The focus on world-class civils produced award-winning work in the tunnelling.
- The focus on world-class design produced extraordinary individual elements (beautiful stations, first-in-class technology, etc.).
- The localised focus on the parts built a bow wave of increasing disaggregation between those parts.
- The failure of 2018 was a shortfall of holistic vision – for how the parts would actually all come together (integration) and work together (operability).

At the start of the recovery phase in early 2019, over 100 leaders within the Crossrail programme (including the supply chain) were interviewed individually to discover their perspectives. The overwhelming majority stated that they knew the programme would struggle to meet the December 2018 date, but could not see the whole, beyond their own component part.

4 Leading in complex major programmes

From the very start of Crossrail, the challenge faced by the Leadership team was very demanding indeed and full of uncertainty. In this section, we look at how the failure of 2018 could have been avoided.

4.1 End dates can be deadly

The adoption of a single fixed end date early in the Crossrail programme is the primary cause of the progressive loss of reality suffered by the Crossrail Board and Leadership team. This was further compounded by the adoption of this as one of the most important outcomes of the programme (the other being staying within the allocated budget). The 'on time and on budget' mantra become the amber that trapped those leading the programme.

If the Leadership team prior to 2019 were afforded the same benefit of planning outcomes in 'windows of uncertainty', as the post-2019 team could, it is the author's view that more thoughtful planning could have been evidenced. For example, the decision in 2014–2015 to proceed with detailed station M&E design before the client's design had reached a pre-agreed level of maturity might have had a different outcome had the concept of 'windows' been in play.

The management of the inevitable tension of pushing the internal team to early dates while maintaining the confidence of sponsors and stakeholders that the late dates will hold is the art of major programme management.

4.2 Owning the whole programme

In a project of this scale and complexity, the primary role of the client organisation is to integrate the activities of many parties. Experience shows that this cannot be left to the supply chain. During the construction phase, contractors working on different stations, for example, can afford to operate somewhat independently. As the project moves into the final phases of integration, ever-greater levels of co-ordination are required. Individual components are tested and verified; then components are integrated, tested and verified in sub-systems; sub-systems are integrated into systems; then many systems are brought together into an integrated operating railway.

This is challenging work, with many frustrations and setbacks along the way. It is vital that the Leadership team can create an environment of 'owning the whole', with a holistic view of all elements of the project and a one-team approach to problem-solving and resource allocation. It is quite literally the case that no one succeeds unless everyone succeeds – as every single piece of the jigsaw must fit together, safely. Completing programmes such as Crossrail are actually not a baton-pass-type race, more a 'Tough Mudder' obstacle course where all parties have to cross the line together.

One of the most critical and successful interventions in early 2019 was the creation of an integration team to bring together the train and signalling software. The very complex, first-of-a-kind software systems for trains and signalling were built by two separate vendors working largely independently. The integration team brought these elements together, co-ordinating and driving integration of the systems as multiple software iterations were developed and tested. In early 2019, software development was regarded as one of the biggest risks to project delivery. The integration team managed that risk and successfully delivered multiple iterations of the software to schedule.

4.3 Creating a culture of collaboration

Another important leadership intervention in 2019 was the creation of forums for collaboration between Crossrail and its key suppliers. It was essential to create a sense of common purpose among the supplier community, and to provide all suppliers with a clear sense of the whole. Again, the need for higher levels of co-ordination made it essential that each contractor was able to see where they fitted into the larger scheme, what the priorities were and how they could work together to solve problems. This intervention was very successful in shifting the productivity and momentum in the programme.

4.4 Reducing complexity and increasing co-ordination

Crossrail is more complex than it needs to be in almost every dimension, including multiple interfaces and dependencies between the 37 main works contractors and their lengthy (and common) supply chains. It comprises very complex technology, as evidenced by the uniquely complex train and signalling system. There are also substantial variations in detailed design station by station, even though the programme started with a very clear ethos of a kit of parts and commonality.

There was very limited use of conscious design modularity and use of off-site construction techniques (Design for Manufacture and Assembly, or DfMA). Far too much construction, testing and integration was done actually in the target infrastructure, often 30m below the streets of London by thousands of interdependent workers faced with very difficult access and logistical constraints.

In part, this was due to a complex procurement strategy with a huge number of contractor interfaces to manage. This was challenging throughout, particularly as the programme moved from construction to testing and integration.

Programmes such as Crossrail are inherently complex; undoubtably decisions made by the programme had the effect of increasing the complexity. In this environment, as complexity increases, there is an ever-increasing need for the client organisation to co-ordinate and integrate activities. The commercial risk/reward framework needs to support and enable this requirement for client organisations such as Crossrail to become expert at co-ordination.

The technical assurance process deployed on Crossrail is, by necessity, complex and of a very large scale. Over 250,000 documents need to be completed to assure the new railway. While there is no doubt the assurance process could have been made more efficient, the key leadership challenge is to actually complete the work. Often this work completion is dependent on several co-dependent parties. Hence the absolute need for greatly increased off-site construction and assurance, and also a continuous and clear-eyed view of the actual extent of completeness.

4.5 Focus on the whole system design and implementation, not just civil engineering

One of the biggest challenges facing major infrastructure projects is the almost Victorian mindset that identifies infrastructure with civil engineering – Crossrail was a system integration programme, with civil engineering as a means to an end, not an end in itself. Crossrail is about delivering the Elizabeth line, a high-quality, safe, reliable, convenient operating railway – not about delivering a set of tunnels and stations. Plans for integration, testing and assurance were poorly understood and unrealistic. Most of the leadership, metrics and reporting were all construction focused, leading to the catastrophic result of vastly underestimating the effort required to bring the whole system together. The key is to genuinely consider the whole system throughout the entire life cycle – particularly at the key decision points. On Crossrail, this was compounded by the millstone of a single end date defined many years before.

5 Recovery

5.1 Building the new team

Towards the end of 2018, a largely new senior Leadership team was put in charge of Crossrail delivery. This was accompanied by a shakeup in governance, with additional sponsor-appointed Non-Executive Directors (NEDs) on the Board, together with a new Chair and Deputy Chair at the start of 2019. The speed with which the new team was put in place was admirable – nevertheless, there is no doubt that a great deal of momentum was lost as these changes were implemented, and as the new team started to create a new plan for completion of the railway.

While the new Leadership team functioned well in challenging circumstances, there were undoubtedly one or two leadership gaps that detracted from the overall performance of the organisation. These gaps were ultimately filled very successfully. But with the benefit of hindsight, we should have moved more quickly to get the correct balance of skills in the team – nothing is more important in the successful delivery of a project than the quality of the leadership. Recognising gaps and moving quickly to address them is vital.

The 2019 Leadership team did, however, gain broad alignment on a plan that mapped out all the parts *together*, and *mobilised* the programme teams to work inside a performance-managed time frame that identified connectivity between the individual parts.

In addition to new leadership, the organisation had to rebuild in several crucial areas. Optimism about the 2018 opening date had led to premature demobilisation of around 30% of the Crossrail organisation, including crucial disciplines such as project controls and risk management. Rebuilding this capability was a critical factor in the speed with which management was able to get the project back under full control.

5.2 Enrolling and activating the supply chain

One of the major dysfunctions on the Crossrail programme leading up to the 2018 problems was the gap in planning and forecasting between the supply chain and the client. The new Leadership team made a particular effort in bringing the supplier community together and enrolling them in owning the whole of the programme's success. This included having the Tier 1s and Tier 2s work more collaboratively, from holistic solutions to deploying scarce specialised resources. Some examples are listed below.

- Transforming the CRL/Siemens/Bombardier collaboration through establishing the 'plateau' approach, where the software 'mountain' was climbed together in small incremental steps but by remaining highly aligned at all times.
- Intervening in the conditions at Bond Street, a particularly challenging element of the programme, through increased alignment and collaboration with the Tier 1 contractor.
- Being clear on the priority and sequence of the entire programme, such that scarce resources at Tier 2 and Tier 3 could be deployed efficiently.

5.3 Rebuilding trust – openness and transparency

One of the major impacts of the missed deadline in 2018 was the total breakdown in trust between the sponsors, stakeholders and Crossrail Ltd. Rightly or wrongly, stakeholders felt badly let down, and in some cases seriously misled. It is not possible for an organisation to function effectively under such conditions, so a primary objective of the new leadership was to rebuild trust. In pursuit of this, the leadership team and the Board committed to a principal value of maximum openness and transparency. This was pursued through a variety of means, including frequent briefings of sponsors and stakeholders, publication of board minutes and Project Representative (P Rep) reports, face-to-face briefing of sponsors at the end of all board meetings, etc., but above all by exhibiting open and transparent behaviour: a willingness to share the bad news as well as the good, and to be open about the risks and uncertainties facing the programme. This is often very difficult, especially in a public setting where uncertainty is frequently construed as incompetence.

Of equal, if not greater, importance was the need to create trust within the Crossrail organisation itself. Establishing clear and transparent flows of information from the bottom of the organisation to the top was vital – this was something that had broken down in 2018. The leadership quickly initiated a visualisation board approach throughout the project, building a matrix of measurable performance indicators to establish progress, identify issues and blockages, and escalate problems as rapidly as possible. This was a critical early step that provided a structured approach to gathering data, tracking progress and solving problems in a uniform manner across all parts of the project. It was a significant step in building a holistic view of the whole project. It also created a shared language and process for performance management, which was a notable gap prior to 2019.

5.4 Rebuilding the plan

One of the most critical interventions at the beginning of 2019 was the creation of a new plan to complete the railway. The new team inherited a plan that was undeliverable, as it was not underpinned by a realistic understanding of the amount of work still to be done. In creating a new plan, known as the Earliest Opening Programme (EOP), the team developed a staged approach to the completion of various elements of the railway, such as the stations. This staged approach allowed vital activities, such as testing of trains and the signalling system, to be carried out before final completion of individual stations.

While the EOP provided a solid foundational logic for the final stages of the project, turning this logic into detailed cost and schedule estimates proved more challenging and took longer than anticipated.

In early 2019, the leadership and the Board were under considerable pressure (to some extent self-imposed) to announce revised cost and schedule estimates. Building on the learning from 2018, the Board elected to publish a range of dates (an opening window) and a range of costs, in recognition of the considerable risk and uncertainty that remained within the project. This was something of a novel approach at the time, but is now becoming well established in projects of this magnitude and complexity.

Despite what we thought at the time was a cautious approach, by publishing a range, initial estimates proved optimistic and had to be revised on two occasions. In early 2019 we had only a partial understanding of what was left to do, and a very incomplete understanding of the productivity we could achieve in the very complex and highly interdependent tasks remaining. A key lesson to be drawn from this experience was the need to resist pressure – whether actual or perceived – to make public statements before the level of information and analysis is sufficient to fully underpin the estimates. The longer-term loss of confidence from failing to meet expectations substantially outweighs the short-term benefit of satisfying stakeholder desire to know when the project will be complete.

Balancing the need for creating new timeline expectations in 2019 with the reality of how much was not understood and not ‘see-able’, in terms of integration and operability, was a key learning at this time.

6 Conclusions

Three key lessons have been distilled from the experience of completing Crossrail.

1 Systems thinking is essential

Perhaps the single biggest lesson from the Crossrail experience is the vital importance of seeing the system as a whole, and recognising that the primary delivery challenge of any large-scale infrastructure project today is not the civil or mechanical engineering, complex though that may be, but the integration of the whole system. For a long period, the primary emphasis of the project was on the extraordinary feats of civil engineering required to build beneath London. These were indeed exceptional accomplishments, well documented and justly praised.

2 Deadlines can be deadly

The fixation on an increasingly unachievable delivery date during 2018 provides another important lesson from the Crossrail experience. One that has already been distilled, reported and acted on by the Department for Transport and the Infrastructure and Projects Authority (DfT and IPA) in their report *Lessons from Transport for the Sponsorship of Major Projects*. While all projects need deadlines to create pace and momentum, total commitment to an unrealistic deadline can create an environment in which the reality of actual performance gets lost. The upward flow of information that contradicts the top-down imperative can be hampered, information is subconsciously shaped to support the prevailing narrative, and serious cognitive bias affects the ability of leaders to see reality and act accordingly.

It's not that there were deadlines, which are a fundamental component of almost every project. Rather, it was the single-minded adherence to deadlines without mapping them onto realistic views of progress – the lack of managing the tension between target and progress. That single-mindedness came from a perspective, either a lack of willingness to confront the objective indicators of insufficient progress or to confront the potential consequences of failing to meet very public objectives. That was failure of perspective and leadership.

Unfortunately, this experience during 2018 did not prevent the new Leadership team from also creating optimistic schedules in 2019, but it did lead to a massive effort to increase transparency in reporting, and to the introduction of the concept of target ranges for cost and schedule, rather than single-point estimates. Essential in this is for the authorising environment around the programme to encourage openness and transparency, and not to shoot the messenger.

3 Complexity kills

A third major lesson from Crossrail relates to complexity. Some degree of complexity is unavoidable in a project of the scope and scale of Crossrail. However, complexity carries enormous cost and creates high levels of risk. Decisions – technical, commercial and organisational – made early in the life of the project created a complex environment for project completion. A determined effort should be made in the conceptual design stages to simplify and standardise to the greatest possible extent. Off-site construction should be encouraged. Modularisation with factory testing of whole systems could greatly simplify the expensive and time-consuming work required on site. There are many other examples.

Most major projects have a fair degree of complexity, and this one set a new standard. The complexity itself might have been (more) manageable if there had been more attention paid to the need to address the programme from a holistic (integrated, owning the whole) perspective.

These lessons and themes have of course been intertwined with the human leadership throughout. Each of these themes, in and of themselves, do not tell the full story of what broke down and what worked (and didn't work). We believe the failures before 2018, and the subsequent interventions, came down in large part to the question of how the people involved perceived and viewed these issues, and how they acted and behaved as a result of that perception.

Prior to 2019, there was a shortfall in how people leading the programme looked at what they were confronted with; a lack of a unifying, integrating, coherent vision for where they were heading that catalysed the issues described in the three lessons above to turn into the blockers they became.

The challenges of Crossrail are systemic in nature and not down to any one individual or groups of individuals. The efforts and achievements of leaders and leadership teams throughout the long history of Crossrail have been remarkable. But the environment could have been created to be even more productive, and also could have avoided the loss of confidence and opportunity that affected the programme in its latter years.

Crossrail programme recovery

1 Introduction

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In early 2020, following the 2018 announcement of significant delay to the opening of Crossrail and the associated cost increases, the Crossrail programme was hit by yet another blow – COVID-19. The programme stopped all work in March 2020 and set about developing a recovery strategy to achieve the original objectives as closely as possible, while working out how to deal with this unknown and unforeseen threat.

In August 2020, the Crossrail Ltd (CRL) Board endorsed a Recovery Strategy and schedule that set targets for Entry into Railways and Other Guided Transport Systems (ROGS) regulations and Trial Running of 26 March 2021, Entry into Passenger Service for the Central Operating Section (COS) in the first half of 2022, partial through running from the Great Eastern and Great Western networks in December 2022 and full through running of 24 trains per hour (tph) in mid-May 2023. Since then, all these objectives have been met, with the programme on target to achieve 24 tph on 21 May 2023.

This paper describes the Crossrail response to the programme challenges experienced since the announcement of the delay to passenger service opening in 2018. There are no groundbreaking or extraordinary insights here; rather, the Crossrail programme's response serves as a case study of how the deployment of programme management tools and recovery techniques can result in an extraordinary outcome despite the challenges.

Three dominant strategic focus areas emerge:

- Generation of a recovery strategy and adjustment to emerging information and threats
- Ongoing evolution of the organisational structure to create the right environment and recruit the right people for the final integration phase of the programme
- The use of management tools, in particular a Delivery Control Schedule (DCS), to control and manage recovery to the committed programme

The success of the recovery programme has been largely down to the willingness of CRL, its stakeholders, and its sponsors to confront new and challenging circumstances, and to adapt quickly. This has been through a combination of organisational change to reflect the transition from civils construction to systems integration and bringing the railway into use, coupled with the creation of an agile recovery strategy. Underpinning this has been the provision of accurate and timely management information on a rigorous four-week reporting cycle, feeding into an overarching Delivery Control Schedule owned from shop floor to CRL Chairman and latterly the Transport for London (TfL) Commissioner.

This paper has been written chronologically to describe the key activities and interventions that the CRL, Rail for London Infrastructure (RfLI), London Underground Ltd (LUL) and MTR joint team implemented to recover the Crossrail programme. It describes some of the key complexities and impacts that affected the programme, and pulls out strategic insights (Blue Boxes), tactical insights or lessons learned (Green Boxes), and identifies risks that affected the CRL recovery programme but could be mitigated on future programmes (Purple Boxes). A summary timeline is presented in Appendix 1, aligning the Recovery Strategy, organisational change and Delivery Control Schedule events.

Finally, these 43 call-outs are refined into 21 summary recommendations, each aligned with the three strategic focus areas above and the Department for Transport (DfT) paper on *Lessons from Transport for the Sponsorship of Major Projects* (see Appendix 3). To the five themes emerging from the DfT sponsorship paper, we propose to add two more programme management themes, creating seven key programme themes for any major programme to consider.

The five DfT sponsorship themes are:

A – Accountability must be unambiguous

B – Behaviours matter more than process

C – Control schedule and benefits as well as cost

D – Deal with systems integration

E – Enter service cautiously

To these we have added two programme management themes:

F – Facilitate investment in leadership and team

G – Generate and maintain an agile delivery strategy that is regularly tested

2 Emerging crisis

Second half of 2018

For the majority of the Crossrail programme, passenger operations were scheduled to open in December 2018; however, in late 2018, it became clear that the programme to deliver this was no longer credible. In response, there were changes to the Chairman, CEO, Executive Management team and Board.

While much has been written about the Crossrail programme in late 2018 and the decisions taken, the following are the undeniable facts.

- The programme schedule in place in December 2018 – the Master Operating and Handover Schedule (MOHS) – was no longer credible and did not contain all the work required to open the railway.
- The Programme Controls team had been largely demobilised, including supporting cost and risk management systems, meaning the quality of management information on which decisions were being made was low.
- There remained a substantial 'orange army' of construction resources with high associated ongoing costs.
- Commercially, the remaining contracts in place had long since lost any target cost incentivisation, and at that time were essentially 'cost plus'.

Collectively, this required a reset of both the organisation and the programme itself. In the first half of 2019, the Crossrail leadership had to balance priorities across the programme and complete strategic planning of the 'Earliest Opening Programme' (EOP), while recruiting an experienced systems integration team to deliver it.

The new CEO set about assembling a team of experienced railway delivery people to augment the talent already working on Crossrail, including people who had commissioned LUL stations, people who had commissioned 24-tph services on the classic network and people who had run major blockades in complex live-railway environments. These people needed to be on board early enough to make sure that the new recovery and staging strategy was robust. This took time and did not conclude until early 2020.

Strategic insight: Programmes go through different phases. Each phase needs a critical review of the organisation to make sure the best and most experienced people for that phase are part of the team. At this time, the programme needed a leadership/management team experienced in commissioning complex railway systems, but it took time to assemble the team.

A Strategic Delivery Office (SDO) was established by the CEO to support the resetting of the programme strategy or 'programme reboot'. This comprised rebuilding the organisation (building capacity and capability across core teams), redesigning and implementing fit-for-purpose governance, and establishing the right management information to diagnose the most critical areas of the programme.

The SDO oversaw activities that included those listed below:

- Setting up a CEO 'War Room', providing ***organisational performance*** management information on rebuilding the Crossrail Ltd organisational capability
- **Executive sprint planning**, where the CRL leadership developed strategic objectives and monitored plans to enable momentum to be created and provide clarity down into the programme organisation
- A review of the '**programme architecture**', which included resetting governance and reviewing meeting objectives, agendas and attendees, to ensure they fitted the new strategy
- **Management coaching and leadership workshops** to support the development of collaborative and winning culture leadership objectives
- **The establishment of enterprise risk** and alignment to TfL's enterprise framework, with 12–20 strategic risks that had Executive ownership and clear mitigation plans
- The introduction of **visual management** to provide ***programme performance*** to reconnect the programme, sub-programmes and projects, providing quantity tracking on asset and assurance completion. When introduced at programme, sub-programme and project levels, it helped build team and stakeholder confidence in the day-to-day delivery of the programme; however, it was recognised as an interim fix while a new baseline recovery plan was established to replace the MOHS

Lesson: At times of major programme recovery, a multidisciplinary SDO is required to deliver organisation development activities concurrently with the resetting of the programme.

Lesson: There is a need for different types of management information at different times in programme recovery. It wasn't possible for a fully re-baselined schedule to be developed before performance management was initiated, as there was a need for near real-time data on what was happening day to day, both around organisational development and around programme performance, to get the programme moving coherently again.

3 The Earliest Opening Programme (EOP)

The new opening strategy (first half of 2019)

The Crossrail programme had a high-level five-stage opening strategy that opened overground to the east and west (Stages 1 and 2), and then opened the COS in three stages: central services between Paddington and Abbey Wood (Stage 3), followed by increasing services and through running east to west and then full through running east and west (Stages 4 and 5). This was a good strategy, and one that, to some extent, mitigated the risk of opening the whole service. However, this treated the complex COS as a single-stage opening. The COS had nine large, brand-new central stations including integrated vent shafts and platform screen doors (PSDs), plus a tenth terminal station (Abbey Wood), five portals, five separate main ventilation shafts and an underground (Communication-Based Train Control) signalling system integrated with the national network signalling systems (European Train Control System and Train Protection and Warning System) at the east and west mainline fringes.

It became clear that this was a massive systems integration challenge and an almost impossible task to bite off in one chunk. Further staging was a necessary next step. This would not be easy because the COS had not been designed for staged opening. This would require agile thinking around systems integration and safety assurance.

In the latter months of 2018, the new Crossrail leadership and Board commissioned work to investigate a minimal viable passenger railway through the COS at opening that met the necessary safety cases but could be implemented in a staged approach to deliver the full COS functionality. Crossrail leadership set out to achieve this as quickly as possible. By January 2019, the CRL Board was presented with and noted the strategy and approach latterly referred to as the Earliest Opening Programme (EOP).

The opening configuration would need to be a safe, assurable, acceptably reliable, maintainable and operationally sustainable railway. A set of *de minimis* requirements were developed that had to be delivered at the opening of the first stage. These are contained in Appendix 2.

A key shift in the mindset of CRL at this time was a focus on the more widely recognised challenges of the software interfaces between train, signalling and the Supervisory Control And Data Acquisition systems (SCADA). The Crossrail response to this was to strengthen and empower the Systems Integration (SI) team that existed within the Technical Directorate and create 'Plateau' teams responsible for managing common configuration states for SI. These teams contained representatives from Crossrail, the Tier 1 contractors and the Infrastructure Managers (IMs). This is covered elsewhere in Crossrail's Learning Legacy: *Crossrail System Integration – The Practicalities of Integrating Europe's Most Complex Rail Project*.

Strategic insight: Technical and programme integration has to be led by the client – you cannot outsource this to Tier 1 contractors and rely on contract clauses to 'make' the supply chain address the millions of issues that emerge on-site as the various elements are integrated.

Strategic insight: Create the right collaborative environments for contractors to work together. CRL implemented 'Plateau 1' for routeway contractors and stakeholders, and then created 'Plateau 2' for station contractors and stakeholders. This is difficult to do after the event, so it needs to be factored into the contracting strategy at the beginning, and should be led by the client. See the paper referenced above for more detail.

In parallel with the top-down EOP strategy, work was ongoing to build bottom-up schedules that would deliver the work to enable the EOP. This bottom-up schedule became the DCS and contained much-improved schedule logic and a clearer view of the work to be delivered. This schedule was subject to scenario analysis and subsequently went live from August 2019 as DCS 1.0. This increased the level of control; however, it remained in places overly optimistic, with challenging deterministic dates set by the project teams themselves, subsequently found to be too challenging regarding productivity and production forecasting accuracy.

The programme's master schedule was rebuilt using project-level forecasts containing no time contingency or time risk allowance (TRA). These were extremely challenging to deliver. As a result, the programme's DCS came under pressure relatively early on. To absorb this, while the underlying confidence in the schedule was improved, the use of 'opening windows' was implemented. Instead of specific target dates for external key milestones, opening windows were published to provide stability while the underlying issues with schedule confidence were rectified. The internal programme control activities managed performance within these windows, targeting achievement as early as possible.

Strategic insight: In times of major programme recovery, there is significant pressure to commit to a single opening date; however, this is inadvisable. To build stakeholder confidence, it's more important to have a reset plan that holds to key date windows and builds confidence, than to be overly optimistic and then have to reforecast frequently.

To gain Board and stakeholder confidence in the EOP and DCS, independent insight and assurance was sought at regular points throughout the recovery. This included a set of third-party expert 'red and black' reviews, where panels were asked to review the schedule (red review) and the commercial and cost positions (black review). The outcomes of this approach were incorporated into the programme controls reporting and the review teams' summary outputs were shared with stakeholders to increase confidence. Later in the programme, Crossrail's assurance function was brought closer to programme activities to provide more progressive real-time assurance.

Lesson: Use third-party independent expert panels and independent assurance proactively and openly at regular points in the programme, to gain sponsor and Board confidence and trust in the new approach.

4 ‘How deep is the hole?’

Handing over the Shafts and Portals (second half of 2019 to February 2020)

The handover of the Shafts and Portals was selected as a test case for the asset handover processes. This was because they were due to be handed over early in the sequence of assets and were considered to be relatively simple compared with the other Crossrail assets. In practice, this brought to light some interface issues concerning how the work was being measured. The civils works contractors were claiming (in schedule and commercial terms) that the work was complete when it was physically installed; however, the Engineering and Operations team was not accepting the work until it had been fully integration-tested and the relevant documentation had been completed. There was a clear mismatch in reporting of ‘completion’ across the disciplines and this exacerbated the lack of trust between project delivery teams and those parties accepting the assets. In many instances, the integration testing and associated documentation required was a ‘many to many’ relationship, meaning that it was hard to track progress accurately without a configured relational database; this was never attained on the programme and so required tactical workarounds.

Lesson: There is a need for a clear and agreed definition of ‘complete’, with common formats for recording status in the relevant management systems across the delivery and acceptance teams. A relational database, mapping the links between completion evidence, is also advisable.

Historically, the Shafts and Portals had been grouped with stations for delivery management, but in reality, they needed to be linked to routeway as they were fully integrated into a number of core routeway systems.

The Shafts and Portals were typical of all elements of the programme in that schedule adherence was consistently and doggedly around 33%, meaning that only a third of the planned activities for any given period were being delivered. Through analysis it was clear that this was driven by complex work interfaces in this phase of the programme. Remaining physical installation locations became much more congested, and the commissioning and testing processes were non-linear and highly integrated.

The delivery window was set between the deterministic date and the dates that had a 50% probability (P50) and an 80% probability (P80) of being met as determined through Quantified Schedule Risk Analysis. Crossrail traditionally performance-managed the programme to deterministic dates (i.e. including no risk) and managed the sponsors and Board to P50. Due to schedule performance issues and the lack of resilience in the plan, the CRL team consistently did not meet deterministic dates, and this had a real impact on team motivation.

Lesson: Delivery plans need to be achievable for teams to buy into them. In subsequent iterations of the DCS, deliberate schedule contingency and ‘fire breaks’ were included as part of the planning logic, which meant it was no longer a zero-probability (P0) delivery schedule and allowed for some flex in delivery. This approach meant schedule forecasts became more stable and supported.

While the works remaining still included some civils elements, such as the tunnel pump drainage, the majority of the remaining effort would be around systems integration.

To support this transition, the delivery philosophy was adapted from one of a construction project with some testing, to one supporting joint priorities – with three days allocated for civils and unit testing, and four days allocated to Dynamic Testing. This required roles and responsibilities to be updated, and the development of the Trace Access Matrix, a co-ordination tool to manage access priorities in four dimensions (including location and time). The governance of the Trace Access Matrix allowed effective triage of trade-offs between different competing demands.

Lesson: Where integration work is complex and integrated, programmatic governance needs to be nimble and adapted to allow controlled but quick decisions about priorities.

A Key Performance Index (KPI) 'tree' was developed to complement traditional programme controls metrics (Schedule Performance Index, Cost Performance Index, Earned Value, etc.) to provide an objective view of progress and performance. It set out a strategic framework aligned to the assets required for 'Entry into Trial Running' (the first configuration state). Each asset was assessed along its value chain to simply lay out the steps it would need to undergo to be ready for the first configuration state (e.g. design, build, test and commission, assure and handover). The aim was to show how each step along the value chain was progressing and the relative performance of each step. Assessing progress at this stage of the programme life cycle was difficult due to the different types of work being undertaken across the railway. As a result, an approach that relied on trusted data to demonstrate performance was taken. The key documents to evidence the completion of each asset were mapped along the value chain, with their status continually tracked to provide an objective view of progress. This KPI tree was a key tool in enabling stakeholders to understand performance across the programme.

Lesson: In areas of programme uncertainty, there is value in creating a single view of the elements of production and quantities across the programme that need to be delivered. Holding this separate to the schedule allows a deliberate focus on the work, not timings.

A key organisational response was to implement project-level Integrated Delivery Teams (IDTs) – which had representation from the various parties involved in delivering, handing over, and subsequently operating and maintaining an asset – and make these jointly responsible for developing and agreeing the project-level plans and managing to them.

This promoted an integrated response at project level, but with up to 30 IDTs at any one time competing for resources and access, it was essential to centralise co-ordination in order to maintain the overall strategic intent. This was required to prevent the individual IDTs ploughing their own furrow, potentially at the expense of others. A strong central 'guiding mind' covering technical, delivery and operations was needed. To provide this, senior CRL executive staff accountable for these areas, including the CRL CEO, met weekly with the leads across the CRL and RfLI organisations to enable the right strategic calls to be made on issues, conflicts and blockers against a single programme strategic objective.

Each single programme strategic objective was carefully chosen to galvanise all organisations and teams around a major programme event that everyone was incentivised to achieve. These were: Entry into Trial Running, managed weekly through the Trial Running Mobilisation Board (TRMB); Entry into Passenger Service, with the TRMB replaced by the Passenger Service Steering Group (PSSG); and Completion of Stage 5, with the PSSG replaced by the Stage 5 Mobilisation and Blockers meeting.

Strategic insight: Where performance is challenging, there needs to be organisational collaboration and joint planning and ownership across delivery, operations and maintenance, to avoid a first-past-the-post mentality, which may often result in sub-optimal decision making. What is best for the programme may require trade-offs at site level across the three disciplines. Weekly strategic sessions led by an independent chair are essential for co-ordination across the programme of individual projects, with a clearly defined strategic objective to galvanise activities around and make prioritisation easier.

To support the delivery of the EOP, the SDO team developed strategic plans to track progress and showcase strategic events that could prevent the programme from achieving its EOP objectives. An End to End (E2E) integrated plan, paired with a detailed description of how the scope should be delivered, was developed through a series of 'right-to-left' planning exercises and through understanding the critical sequences from the DCS. CRL leadership referred to these exercises as the 'backwards pass' approach, the name given to strategic right-to-left planning.

'Backwards pass' sessions were conducted with leadership and key programme representatives to further enhance the collective understanding of specific entry and exit criteria, and 'what needs to be true' to achieve programme milestones. The focus was working back from Stage 5 (through running), Stages 4 and 3 (operation in the COS), Trial Operations, Trial Running, and Entry into ROGS.

Strategic insight: The schedule must be assessed against 'right-to-left' logic testing, not the classic 'left-to-right' approach. Start with Entry into Passenger Service, Trial Operations, Trial Running, assurance, testing and commissioning and so on. The CRL schedule pre-2019 totally underestimated the system integration requirements, despite this being the most complex digital railway ever delivered. It needed a significant amount of time for all the various systems to be brought online.

Lesson: Overall, this 'horizon-scanning' approach, built on 'backward pass' workshops and a strategic E2E plan, was a valuable adjunct to the day-to-day controls cadence. As a whole, it would be appropriate to deploy 5–10% of total programme control resources to this activity, ring-fenced from the day-to-day business-as-usual (BAU) control activities. Without this ring-fencing, the ability to think and plan strategically is reduced by the need to 'firefight', which tended to be required over long periods.

As a result of this long-term view, Crossrail executives were able to have a clear understanding of the overall upcoming challenges and gaps to be addressed, enabling them to increase the maturity of the plan and grow confidence in the deliverability of the programme. The development of the E2E plan (and the application of 'backwards pass' workshops to develop it in detail) was separate to the development of the DCS baseline. The outcomes identified in the E2E plan supported the DCS, but they were ultimately two separate artefacts that were used in parallel. The E2E focused on strategic requirements for achieving subsequent stages of the programme (i.e. achieving sufficient reliability for Entry into Trial Operations), while the DCS tracked and measured the activities that needed to be delivered to achieve that requirement (i.e. specific days when the COS was used for Dynamic Tests).

This overarching E2E plan also helped provide the delivery teams with an understanding of the bigger picture and the value that their work brought in delivering the Elizabeth line.

This strategic work also enabled Crossrail to develop a horizon-scanning approach that was used as the Executive and senior management's tool to promote thinking beyond the next target or milestone. Through horizon scanning, 'what if' scenarios were developed to identify 'hotspots' and mitigations, allowing the deployment of interventions as early as possible to rectify off-track trajectories.

Crossrail benefited from these approaches in several ways, from increasing co-ordination and integration across delivery organisations and the operator, to early resolution of long-term risks, releasing pressure from day-to-day operations, allowing CRL to focus its attention on the bigger picture.

As part of this work, the SDO also performed 'heuristic' risk analysis in parallel. This responded to stakeholder concerns about the veracity of the bottom-up probabilistic programme controls-derived data. This alternative approach looked at circa five mega risks (train reliability, software, etc.), and looked at a mixture of scenarios to get best- and worst-case outcomes, plus some interim scenarios. This was referred to as 'headwinds and tailwinds' analysis.

Lesson: 'Heuristic' risk analysis proved a better approach than standard QSRA/QCRA analysis when engaging meaningfully on the recovery programme with the Board and sponsors.

At the beginning of 2020, the final pieces of the Executive and Systems Integration Delivery team were put in place. A new Chief Programme Officer was appointed, along with a new Chief Finance Officer to complete the CRL Executive team, and new appointments were made to provide strength and depth to railway systems integration and commissioning knowledge in the delivery functions.

From January 2020, before the impact of COVID-19, there were delivery performance issues – especially in the Shafts and Portals and stations – that were manifesting as schedule slippage. The approaching COVID-19 pandemic would further exacerbate this schedule pressure.

5 COVID-19 crisis

Stop, restart and an opportunity for a new strategic approach: March to June 2020

In March 2020, at the time of the first COVID-19 lockdown, CRL instigated a Safe Stop for all works on the Crossrail programme. While this was a very difficult decision to take, it was a necessary step to protect the workforce. It was also a golden opportunity to put our foot on the ball and take a step back to reappraise the situation. More than 4,000 people had been working on the programme up to that point, with poor productivity reported (around 33%). The SDO migrated into the Silver Recovery teams.

CRL immediately implemented a 'working from home' policy for everyone except those absolutely required at site. This helped manage the initial threat, with regular personnel updates via Zoom calls to keep the workforce updated on the developing events.

Strategic insight: 'Never waste a crisis'. COVID-19, while terrible for the country, was an opportunity to reset the programme. Don't be afraid to stop and reset the programme if the circumstances dictate. Harness the talent that was too busy fighting the fires and set it to work to strategically solve the route to closure and, in doing so, tackle the crisis.

At this point, the programme was moving into the assurance stage with assurance activities on the critical path. The Elizabeth line is a highly complex integrated digital railway. On top of that, the level of effort required for the assurance pyramid was a huge challenge. We were assuring a brand-new railway for the Office of Rail and Road (ORR) as well as the standing-up of a new Infrastructure Manager (RfLI). The CRL Executive members had to chair assurance close-out forums, not a common requirement on established networks such as Network Rail and London Underground.

As a result, significant assurance documentation was required for the regulators to authorise the railway to be placed into passenger service. Working from home suited these activities and allowed staff to focus and concentrate on generation of the completion paperwork. The extra time at the beginning and end of the day gained from not commuting (two to four hours) aided this, but those members of staff with young families were particularly impacted, with some opting to return to the office in order to work effectively. This was managed in a controlled way to minimise risk to our personnel, both from a COVID-19 and wellbeing perspective.

Lesson: Quick development and deployment of new working rules, with an opportunity for exceptions to be granted in a controlled way, assisted the programme recovery. Gold, silver and bronze command levels were set up and led by programme personnel. Weekly reviews adjusted the programme approach.

Once new COVID-19 safe-site protocols had been determined, teams were only allowed to start with defined works packages and areas of work that maintained social distancing and observed the COVID-19 guidelines. This was an opportunity to exert absolute control on the deployment of personnel. Safe working rules meant work could be delivered more efficiently, but over a longer time frame. Previously congested work fronts were now easier to work in. The workforce reduced from over 4,000 to around 2,000 under controlled deployment, which improved cost control.

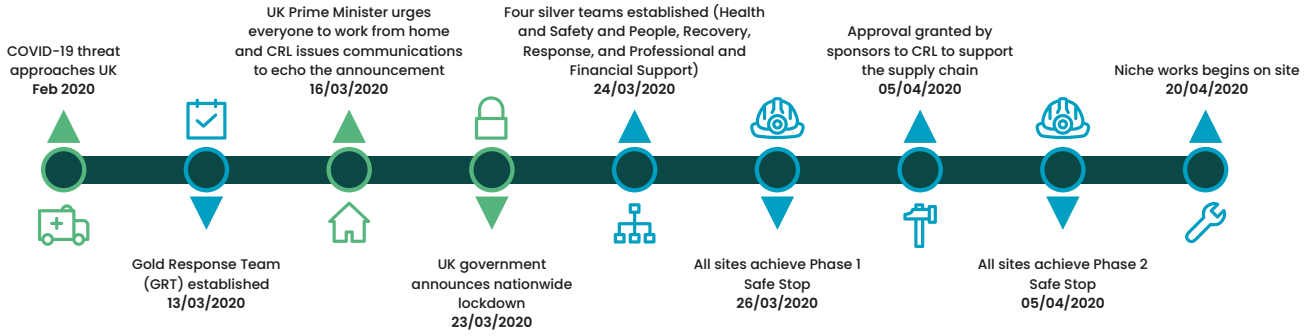


Figure 1 The impact of COVID-19 on the CRL programme

Dynamic Testing with the trains was restarted once agreement with ASLEF was reached (a maximum of eight staff on any train, only two personnel allowed in the cab and socially distanced welfare arrangements in place). This was a low COVID-19 risk activity but had high impact on programme achievement, allowing the high-level schedule to be maintained while replanning to absorb the COVID-19 impact elsewhere.

With the complete uncertainty that COVID-19 brought, the recovery team used techniques to describe the range of impacts that COVID-19 could have. This was characterised by using 'Dials of Disruption' to describe potential COVID-19 scenarios and articulate the potential impact of COVID-19 disruption on the Crossrail programme as the severity or longevity of disruption increased. Figure 2 is a snapshot of the thinking from April 2020.

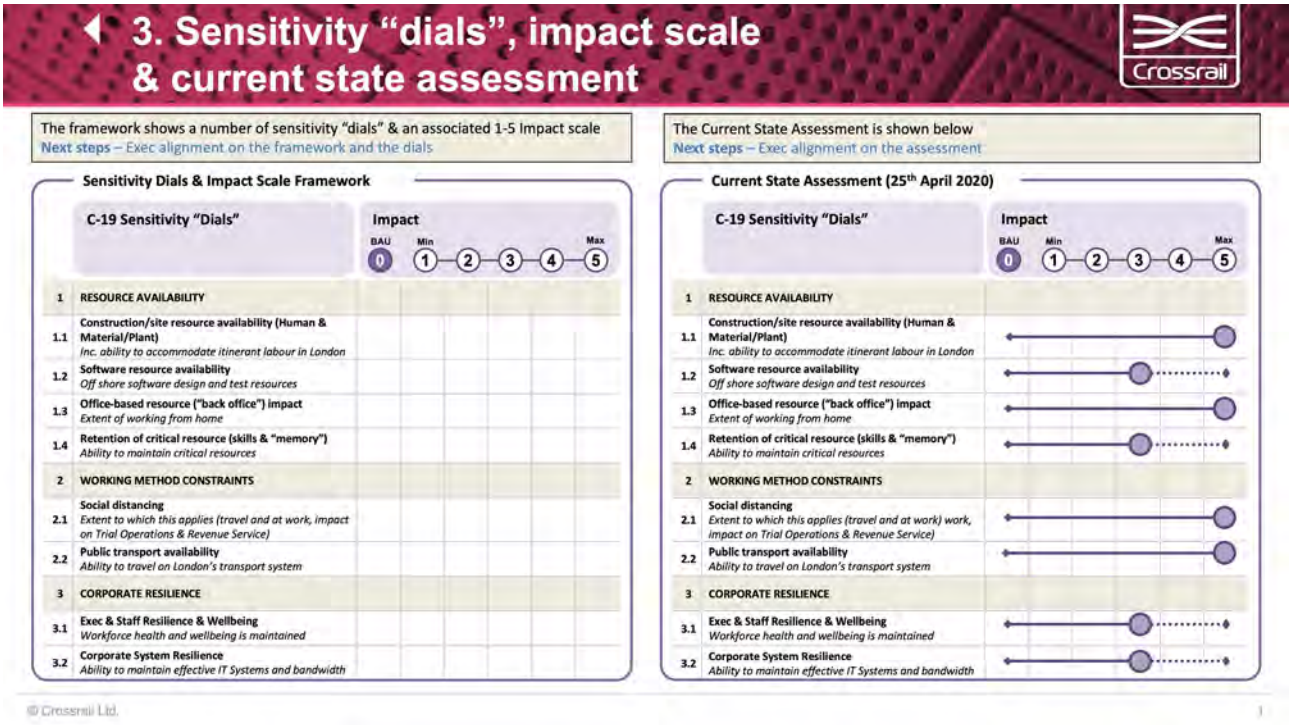


Figure 2 The 'Dials of Disruption'

Describing an unknown threat in terms of its potential impact helped manage the uncertainty and develop the necessary short-, medium- and long-term mitigation plans. This then provided reassurance to the Board and sponsors that the mitigation plans could be deployed to restart safely.

Lesson: Describing the likely impact of a threat on the programme and how it varies (rather than attempting to characterise the unknown threat) quickly led to the identification of the required mitigation plans.

The short-, medium- and long-term mitigation plans assured the sponsors, Board and Non-Executive Directors that CRL was in control, while we developed the outline recovery strategy and revised the DCS.

The Panel of Independent Strategic Advisors retained by the CRL Board facilitated engagement with other UK programmes and operators (Hinkley Point, Network Rail, Sellafield, Thames Tideway and HS2) to learn about how others were handling COVID-19 impacts. Their independent review of the mitigation plans in place, added to the adoption of best practice from other programmes, gave confidence that we were applying or adopting best practice while dealing with this threat. The panel provided a vital role throughout programme recovery, being deployed as individual subject-matter experts or as a panel, by critically and independently reviewing key aspects of the programme and advising the executive and Board.

Strategic insight: Retaining a panel of independent strategic advisors that can be deployed quickly on key programme issues provides independent critical and experienced advice to the Board, Executive and senior leaders in the programme. This can be crucial when steering a recovery programme through uncharted waters.

Lesson: To record the emerging schedule, the DCS was modified under change control to reflect the emerging strategy; this was characterised as DCS 1.1, which was not a wholesale change but a significant departure from DCS 1.0 (the EOP). To provide confidence to the assurance teams (Lines of Defence 2 and 3), the programme adopted a DCS Maturity Matrix to increase transparency of schedule quality, and improve the maturity of the schedule discussions with the assurance team, Board and sponsors against specific modules of the recovery strategy.

The COVID-19 pandemic allowed the programme to reassess the software deployment programme and identify more advantageous software configurations that would improve the outcomes of the testing. This was both in terms of verifying better, more mature software configurations, but also by identifying earlier – through Dynamic Testing – the key issues to resolve from an operator point of view.

Programme controls and periodic reporting were a dominant part of the recovery approach. The regular four-week reporting cycle kept people focused on the programme and the issues, while providing good management information to validate the schedule and approach, or adjust it as required. This also gave confidence to the Board, sponsors and stakeholders that the recovery plan was working. Visual management was operating in support, but it is no substitute for a well-constructed and resourced schedule that is bought into by all levels of the programme.

Lesson: Key points from this period are:

- Use of the 'Black Swan' crisis event (COVID-19) as an opportunity to reassess the programme, e.g. software upgrade availability and opportunity for better configurations to be deployed at key stages, reducing risk
- Taking advantage of the medium- to long-term uncertainty to set an achievable near-term objective (Entry into Trial Running) that the programme could be galvanised around, while gathering intelligence on longer-term COVID-19 impacts on programme capability to firm up later stages
- Focusing on finishing the Shafts, Portals and routeway – 'the pipe' – first to complete the initial Dynamic Testing for software development, then finishing stations
- The switch from a split week sharing construction works with Dynamic Testing on a four-day/three-day split, to longer Dynamic Testing windows (weeks/months) with a blockade approach for concentrated works delivered with meticulous planning (hour-by-hour activity scheduling and reporting)
- The use of planned firebreaks to absorb any poor performance or unexpected outcomes

6 A new approach

Solidifying scope, increased productivity and emerging confidence: the second half of 2020

The COVID-19 Recovery Strategy was developed as a set of 10 modules, each with a senior programme owner. It was written as a complete document with integrated strategies for each module (Routeway Delivery, Station Delivery, Testing and Commissioning strategy, Ops Readiness, etc.). Writing the complete strategy down helped capture all the work, and determine and iron out any discrepancies between the individual modules and module owners. The plans for each module were used to develop the DCS 1.1. These were then critically reviewed through an internal assurance process.

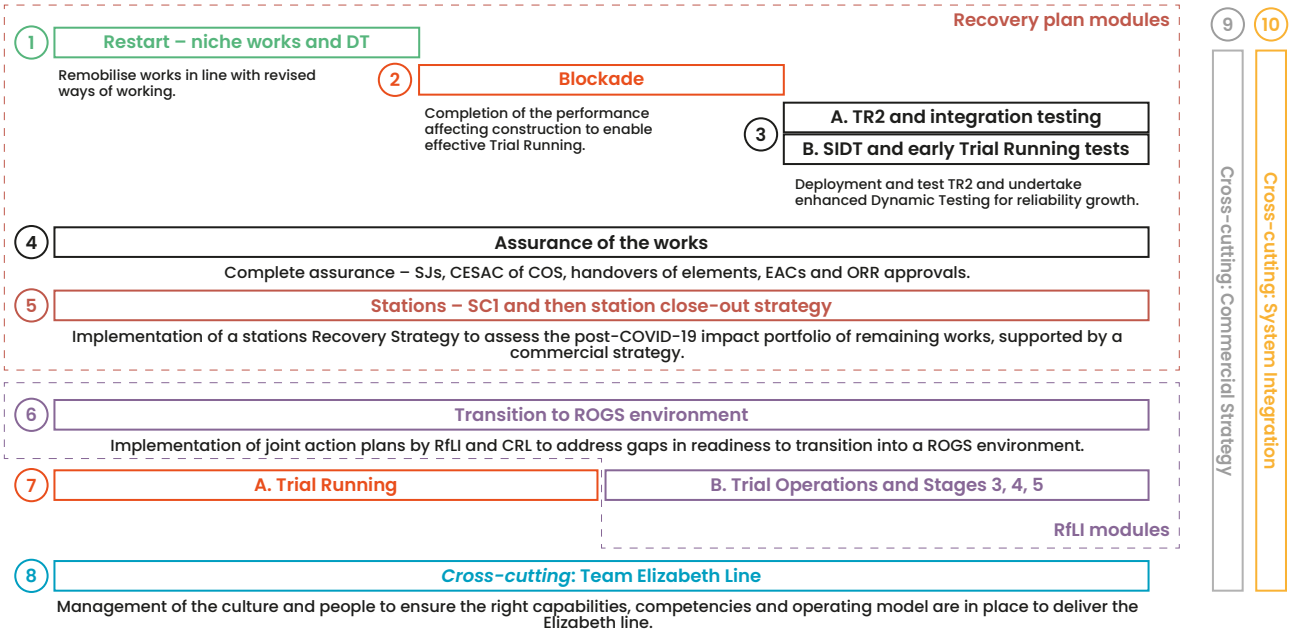


Figure 3 The 10 modules in the COVID-19 Recovery Strategy

Assurance at CRL followed the classic 'three Lines of Defence' (LoD) approach, where LoD 1 consisted of internal peer-on-peer checks and validation, LoD 2 consisted of semi-independent assurance and challenge, and LoD 3 consisted of independent and external assurance. LoD 1 checks were presented to the LoD 2 team, who reported their findings to the CLR Executive, CRL Board and Commissioner. LoD3 reports were issued and published externally.

The progressive and semi-independent LoD 2 assurance review carried out on the Recovery Strategy and DCS 1.1 gave confidence to the Board and sponsors that the plan was credible. While not agreeing with everything in the Recovery Strategy, a constructive dialogue between the programme team and the LoD 2 team identified and resolved weaknesses and built-in recommendations from previous LoD 2 reviews (for example, ensuring contractor and stakeholder involvement and buy-in to the emerging schedule before baselining).

The schedule implications of each module were incorporated into the emerging DCS 1.1, and this was used for the Quantified Schedule Risk Analysis that determined the opening window.

Lesson: By applying a rigorous project management approach to the programme and writing down a coherent strategy in this time of high uncertainty, we were able to describe a strategy that all stakeholders could get behind and focus on, even if only in the short term until Trial Running. LoD 2 review and engagement helped deliver a more robust approach and give confidence to the Board.

As the modules were developed, the DCS reflected the emerging activities from all the partners, not just CRL and the IM and operator RfLI, but also the train operator MTR. This would continue with each DCS refinement (DCS 1.2 and DCS 1.3), building more transparency and linkages into the strategy.

Strategic insight: The schedule baseline has to reflect all of the work, which includes not just the physical, but also testing, rework and assurance activities. Productivity needs to be factored into the schedule times and productivity will be a function of the environment the leadership creates. The paperwork mountain is as big as the physical one, but is often left until the end. It needs to be progressed in real time as the job is built.

A key technique deployed as part of the strategy was the use of a 'blockade approach' used on national network projects for focused construction delivery. This required meticulous planning against a fixed scope of works, refined into a set of activities that were planned on an hour-by-hour basis through the blockade. The blockades could be between one and nine weeks long, but all had to adopt the same rigorous approach. Despite some initial scepticism, the blockades deployed in the summer of 2020 achieved productivity levels of over 95% and allowed Dynamic Testing to be carried out in the periods around the blockades, facilitating efficient and effective testing periods. This performance underpinned the credibility of the recovery strategy and gave further confidence to the Board.

Strategic insight: Demonstrated performance does not lie; CRL productivity was typically 33% against the planned activities between 2019 and the start of 2020, so slippage was constant. The leadership had to recognise this and act, either by accepting it and reflecting it in the time allowances or by changing the environment. We introduced a blockade strategy to complete the works in the routeway, which raised productivity for the works undertaken in that environment to 95–100%. This was because the whole programme galvanised to deliver this level of output (planning, logistics, management, reporting, etc.).

Lesson: While detailed hour-by-hour planning is usually unsustainable for long periods, for short periods of intense well-planned activity it can deliver extremely high levels of productivity, freeing up time for other activities such as testing and commissioning or Trial Running.

The programme management leadership continued to drive better schedule adherence through the deployment of simple productivity measurements via the Programme Controls team. Each period, the achievement of 'start activities on time' and 'finish activities on time'

was measured for each project, and a league table was published that all projects could see. The final handover deliverables were also monitored on simple Red/Amber/Green (RAG) status tables and published as a complete set for all projects in each period. This visibility and clarity allowed the senior management team to focus on the key areas that needed help, and the projects to gauge how they were doing against each other. As a result, schedule adherence in between blockades rose from 33% to around 70%.

Lesson: Simple project metrics and management information for key deliverables compared across projects and discussed at executive level on a periodic basis can galvanise teams into improving delivery in key areas.

As part of the Recovery Strategy, the delivery schedule for the 10 COS stations was critically reviewed. The EOP had assumed that the stations could be brought online two at a time, two weeks apart. Resource-loading the schedule for critical resources such as Fire Engineers and Commissioning and Testing Engineers showed that this could not be achieved. A 12-week T-minus station commissioning countdown process was enforced for each station, with an associated critical resource assessment to 'spread' station commissioning out in order to not overload key resources (engineering/technical/control and communications). This helped justify moving from two stations every two weeks prior to commencement of Trial Running to a more streamlined and resource-supportable programme of a station every 12 weeks during Trial Running, with an overlap of four to six weeks between stations from March 2021. All stations, with the exception of Bond Street, would achieve 'SC3ROGS' (see Appendix 1) by Entry into Revenue Service.

Lesson: Assess what has to be delivered as a minimum for any cardinal milestone (e.g. Trial Running under ROGS) and reschedule the rest using critical resource levelling to create a more sustainable programme.

Strategic insight: A staged opening strategy, with opening windows driven by prioritisation, is a more pragmatic way to deliver a complex, highly digital, first-in-class system such as Crossrail. In the case of Crossrail, commissioning the routeway plus shafts and portals first (the pipe) and then commissioning the stations onto the pipe in two 'swim lanes' – RfLI stations and LUL stations – enabled the teams to understand the prioritisation needed when we had resource clashes or access priority calls to make. When set, this needs to be communicated to the teams, contractors, sponsors and the Board.

As part of the review, it was clear that two of the stations – Canary Wharf and Bond Street – would struggle to be integrated and ready in line with the operators' standards and revised programme. As a result of COVID-19 and given the volume of works still outstanding, CRL took the difficult decision to bring the delivery of these two stations in house; CRL and its partners had sufficient strength and depth to do this. As other stations were delivered, key personnel were switched from these stations to lead the completion of Canary Wharf and Bond Street.

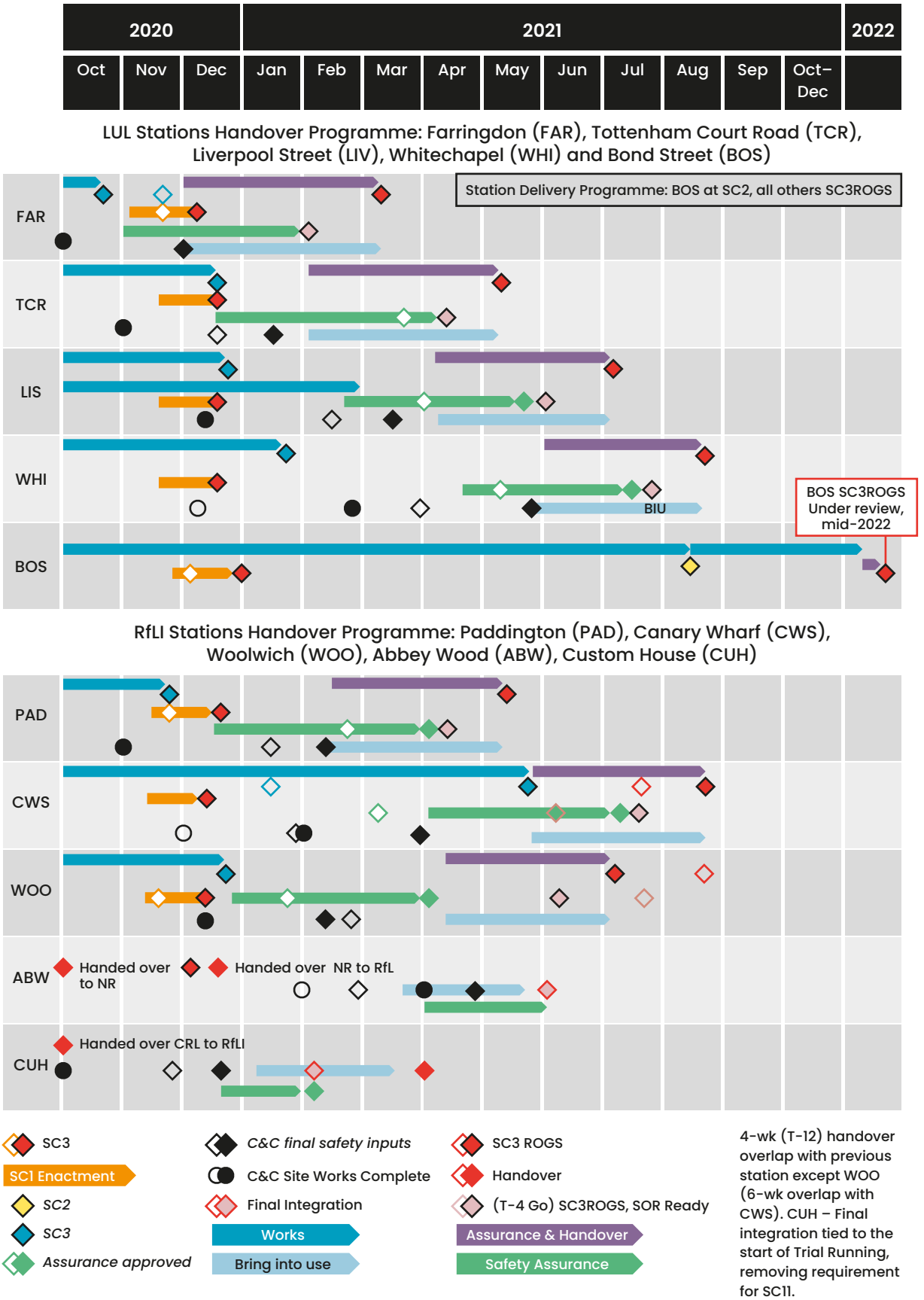


Figure 4 Emerging Stations Deterministic* Delivery Programme @November 2020
(* no client contingency added)

Regular touch points with executives and the Board at key events helped build confidence that we were developing a credible plan. At the May Board meeting, the outline Recovery Strategy received support. At the June Board meeting, the routeway recovery strategy (essentially for Trial Running) was approved. At the July Board meeting, the stations recovery strategy was approved, which comprised a 'swim lane' for LUL stations and a separate swim lane for RfLI stations, and a proposed staggering of the T-minus process to handover. At the August Board meeting, the DCS 1.1 and the supporting Recovery Strategy were endorsed subject to action close-out, and these were then signed off at the September 2020 Board meeting with LoD 2 assurance commentary. Figure 5 compares the overall DCS 1.1 recovery plan with the actual milestones achieved.

Notwithstanding the impacts of COVID-19, a significant amount was achieved over the summer of 2020. The Shafts and Portals team was expected to achieve full handover by early November 2020. The train and signalling software had progressed well, with signalling software TR2 ready to be tested on the COS from early September for multi-train testing in defined windows during the blockade. Routeway assurance (Engineering Safety Justification) submissions had been completed and the major blockade was being successfully delivered.

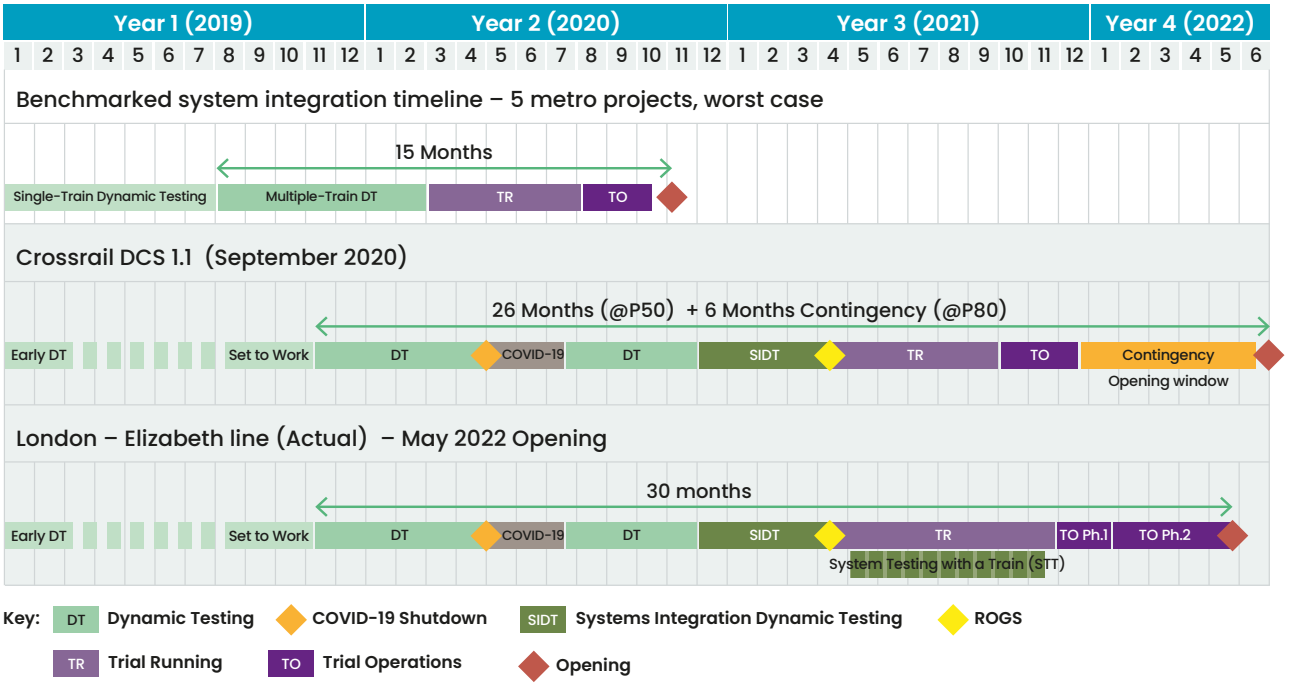


Figure 5 Comparison of DCS 1.1, approved by the CRL Board in September 2020, with the achieved programme

The DCS1.1 became the main recovery close-out plan for Crossrail. It would have two subsequent updates to reflect the actual position following major milestones (Start of Trial Running and commencement of Stage 3 passenger services in the COS). It took approximately six months for DCS 1.1 to go from the start of COVID-19 recovery planning to Board approval in the early autumn of 2020.

In September 2020, a new TfL Commissioner was appointed. The Commissioner made it clear that for the Elizabeth line to be delivered successfully as soon as practicable, it was essential that Crossrail join the TfL fold and the CRL Board was stood down. This was agreed and the process of TfL pulling the Elizabeth line into the estate was accelerated. The CRL CEO now reported to the TfL Commissioner.

Within days, a new client focus was in place, with weekly and then daily Commissioner calls to monitor progress and confirm delivery against the plan, or agree changes to the strategy. The CRL Board was replaced with the Elizabeth Line Delivery Group (ELDG), chaired by the Commissioner. As a result, the CRL Executive was able to get decisions from the Commissioner on a weekly basis, rather than previous four-week Board cycles.

Strategic insight: With the ultimate client pulling the Elizabeth line into the TfL estate, a new client focus and drive facilitated quick assimilation of information and agreement to make strategic changes to the Recovery Strategy.

7 From civils to systems

Testing and asset handovers: first half of 2021

With the review of the available software configurations against the revised DCS, a more developed software configuration was identified as a suitable candidate for Dynamic Testing (DT). At the same time, an application to the Office of Rail and Road (ORR) was made to increase the number of available test trains from four to eight in any one test period. The increased train availability improved the testing confidence and achieved the test and commissioning programme earlier, such that an augmented testing period – System Integration Dynamic Testing (SIDT) – was agreed to be deployed early in December 2020. Critically, this allowed systems integration testing to be performed with a train early enough in the revised schedule to affect software design for the configurations that would be deployed for Trial Operations the following year. The test results in December 2020 identified issues and fixes required to inform design of the later software deployments for Trial Operations and beyond. Safety approval cycles for critical safety systems can take up to six months, so early systems integration testing is essential to identify any major software updates required.

Lesson: By providing a period of System Integrated Dynamic Testing with a train early enough in the programme (approximately a year in advance), software bugs that would affect the Trial Operations phase could be captured and incorporated into the software cycle so as not to delay Trial Operations.

Strategic insight: Plan for rework because it will happen. Client inspections will generate rework. Software drops will experience regression, so factor these into your schedules so that plans have resilience. Plans also need the float to be visible (float is not client contingency), especially when there are handovers between contractors.

A key LoD 2 recommendation from the earlier EOP assurance reviews was to get suppliers to underwrite the schedule and commit to it. All the individual project schedules were discussed and developed with the relevant contractors, and the overall programme received endorsement at the supplier forums.

Strategic insight: Supplier engagement in the development of a recovery plan is essential to underpin its success. Further regular engagement is also essential to continue this support in the face of a continuing external threat.

As part of the development of a transparent weekly reporting pack, the programme management leadership team moved project controls from historic 'reporting what's happened' to forward-looking 'forecasts and burndown curve' predictions. This data was summarised into a weekly reporting pack that went to all stakeholders including the Commissioner, the Mayor's Office and No. 10.

This high-level transparency helped drive delivery focus and completion against future promises rather than historic completion.

Lesson: Management of the IDTs in weekly, short, sharp (30-minute) updates for handover deliverables listed on forward-looking delivery date trackers and planned-versus-actual burndown curves was essential to drive completion. Sharing this simple graphical management information with the programme extended leadership team, all the way up to the Commissioner and beyond, underpinned its importance.

For major milestones the programme employed a rigorous, detailed T-minus process to get to Trial Running under ROGS. This covered all aspects of the railway – reliability, operations, maintenance, assurance, etc. – and each Directorate in CRL and RfLI had readiness questions to report on each week. Each question was designed as a 'closed' yes/no question to prevent ambiguity and drive towards affirming readiness. The deterministic date for the start of the Trial Running period, as set in the Recovery Strategy DCS 1.1, was achieved on 26 March 2021. Achieving this milestone against the deterministic plan was hugely significant. It signalled the end of the railway being managed under the Construction Rule Book and the start of it being managed under the ROGS rule book. Basically, the COS now needed to be treated as a fully operational railway, just with no passengers. However, Trial Running main activities could not start immediately as RfLI needed further familiarisation on the handed-over assets. Full Trial Running did not start for a further six weeks. The movement into a ROGS environment was a huge step for the programme and truly galvanised all parties to push on towards starting Trial Operations, and opening the COS in the first half of 2022.

Strategic insight: The programme delivery leadership needs to think like a maintainer and operator – what is important to it, what will impact on the traffic managers in charge of signalling and control and communications in terms of operational restrictions – and focus on minimising them. The best protection for this is to get the operations and maintenance organisations fully bought into the strategies and the scheme designs during the early development of the engineering 'V' life cycle, then hold joint 'T-minus' countdown reviews with operations and maintenance for all major commissionings on the railway.

Risk for future programmes: Make sure all receiving organisations or parties have sufficient time to prepare and rehearse for taking on responsibility for the new product or service. While RfLI Operations had instigated a four-week period of 4 tph at the start of Trial Running to get up to speed, RfLI Maintenance had not been given sufficient opportunity to familiarise themselves with the integrated operational railway. Future programmes should allow for all receiving parties to adequately prepare, and this readiness should be tested in good time.

8 Light at the end of the tunnel

Trial Running and Trial Operations (late 2021 and early 2022)

The programme achieved Trial Running under ROGS on the deterministic date of 26 March 2021, which had been set in the Recovery Strategy in 2020. However, it was clear from the work done in 2020 that there were still significant delivery issues to be faced. Rather than continue with the DCS 1.1 as set in 2020, the decision was taken to reset the DCS (DCS 1.2) to reflect the new information available (work to go/resources available/access constraints) and structure the programme to achieve the original stated intention of opening in the first half of 2022 but sequencing the work to the available resource.

Strategic insight: Reset the schedule when sufficient information is available to support this, spending time to spread the workload to achieve the original opening window. This maintains supplier and workforce confidence while maintaining the vision.

Even though the programme had more certainty, the CRL Executive decided to maintain the opening window as before and not narrow it down. This was driven by the regular QSRA analysis, which backed up the date range, plus the recurring waves of COVID-19 mutations and the concern that a more virulent strain could affect programme completion.

Strategic insight: Resist the temptation to narrow to a date for opening when significant uncertainty still exists in the programme.

With the implementation of Trial Running under ROGS, access onto the railway became significantly more difficult for many reasons, the key ones being:

- control of the railway had to be placed under the new operator under ROGS regulations
- construction and testing access on the operating railway had to be applied for and agreed under a new Rule Book
- the emphasis switched from construction priority to operational priority
- a new operational team was getting to grips with operating a new and highly digital railway

All of this took time to embed. CRL maintained a strong access management team that knew the railway and could ensure access was applied for and obtained in good time.

Some desktop exercises were carried out, but only to validate the operator processes and resource levels for the operation. Significant shortfalls in safety and track access resource competent under the new Rule Book at the start of Trial Running hampered access for the project to complete the works.

Strategic insight: Recognise the potential for lower productivity when you move from a construction railway to a fully operational railway under ROGS. Access becomes constrained; you need to retrain the whole construction workforce and productivity drops unless you plan for it.

Risk to future programmes: If a new Rule Book and operator are taking over the railway or integrated system, the Rule Book should be critically reviewed to ensure a pragmatic approach has been adopted, and that the benefits of the new infrastructure have been correctly reflected in the rules *before* implementation. Rehearsals and desktop exercises should be carried out as a minimum in the 12-week run-up to Trial Running, with coaching provided by the delivery teams. For example, there was a significant increase in electrical switching operations during Trial Running and Trial Operations compared with the construction period. This was because the Rule Book required full electrical isolation for all activities on the trace. This was implemented through manual switching, even though the system had autoswitching functionality that completed switching in minutes. Manual switching took longer and reduced the overnight productive hours available during 2021 and the first half of 2022. Autoswitching was not standard until mid-2022.

From a programme point of view, Trial Running was characterised by key activities: handover of major stations on a drumbeat 12-week cycle, integration testing of the systems as the number of trains per hour was increased from 4 to 12, and identification and resolution of systems integration issues.

With the transition from construction site to operational railway, sponsorship of the weekly strategic guiding mind meetings (TRMB) moved from Crossrail delivery to RfLI Operations with the setting-up of the PSSG. Further, the weekly T-minus readiness reviews previously chaired by the CRL Chief Programme Officer were now chaired by the RfLI Chief Operating Officer.

One key area underestimated in impact and importance for overall Crossrail systems integration was the tunnel ventilation system (TVS). This was significant because:

- personnel could not gain access to the TVS rooms in the airpath to complete works and test and commission other systems unless the TVS system was isolated in a similar way to the electrical systems
- the TVS impacted the operation of the PSDs as the air pressure changed depending on the TVS settings. When set at full design 'congestion' mode for maximum ventilation, some PSDs did not operate because of the air pressure
- when trains operated in close headway, this caused fan stalling at certain TVS settings

Risk to future programmes: Identify all critical and highly integrated systems. Treat all of them as critical safety systems. Complete all works, testing and commissioning of other systems components in these critical system rooms (where possible) before full commissioning. Allow time to carry out integration tests where the key operational variables (e.g. fan speeds) are varied to establish the failure point for any other integrated systems (e.g. PSDs), and calibrate the system settings to prevent this before handing over to the operator. Resolving these issues during Trial Running, Trial Operations and Passenger Service takes longer and costs more the later they are left.

With the completion of Trial Running and the System Integration tests, the countdown to Trial Operations was initiated. The intention to enter full Trial Operations exercises from the start – e.g. mass evacuation exercises at the stations – was critically reviewed as the systems integration testing had highlighted a number of deficiencies that needed rectifying before 'non-staff' volunteers could be allowed onto the railway. The Trial Operations programme was recast, with low-impact Trial Operations exercises completed prior to commencement of a Part 2 Trial Operations period for the more intensive exercises, which required non-staff volunteers.

Lesson: The Trial Operations period can be a potential programme firebreak; however, it is essential to make sure that the early Trial Operations activities can be completed while the final systems integration issues are ironed out.

9 Crossing the winning line together

Following the successful completion of Trial Operations, the COS opened to service on 24 May 2022, within the opening window defined in the DCS 1.1 recovery strategy. While the deterministic start of the Trial Running period had been achieved against the deterministic plan, Trial Running and Trial Operations had proven more difficult to close out as CRL continued to resolve complex software integration issues, and operations and maintenance teams learned how best to utilise this new railway. The use of an opening window informed by schedule risk assessments has proven a credible way of managing a programme towards the delivery of a major opening event milestone.

The DCS 1.1 targeted the commencement of passenger services in the COS with 12 tph services, nine stations open to passengers and Bond Street station at SC2 configuration, which meant it was available for emergency evacuation only. That is what was delivered on 24 May 2022.

With the programme converging on an opening date, the decision was taken to recast the DCS once again as the ownership passed from the delivery team at Crossrail to the operator for delivery of Phases 4 and 5 of the programme. This was because the final phases would be driven more by operator performance and timetabling than construction completion. As a result, DCS 1.3 was 'owned' by the Elizabeth line Director rather than CRL's Chief Programme Officer following passenger service opening on 24 May 2022. Philosophically, the programme had moved from a delivery 'baton pass' to operations at system handover to the joint teams crossing the winning line together. The baton pass happened in the weekly strategic 'guiding mind' and 'T-minus review' sessions.

Indeed, at the start of 2022, the Elizabeth line Director developed a revised Post-Stage 3 Stageworks strategy by implementing a two-part Stage 5, which would realise benefits earlier. These are known as Stage 5B Minus and Stage 5C. On 6 November 2022, the programme successfully delivered the next stage (Stage 5B Minus with 22 tph through running) on time, with forecasts for the final stage (Stage 5C with 24 tph) holding at the mid-May 2023 timetable change date.

Lesson: At each phase of the programme, the overall End-to-End schedule should be owned and maintained by the organisation with the most influence on its ability to delivered.

As the station contracts were driven to closure, CRL recycled the experienced personnel coming free from other stations to be involved in a bottom-up review of the Bond Street station delivery schedule to confirm a realistic programme for opening. The re-baselined Bond Street station schedule was approved in February 2022, with an opening window of November 2022 to February 2023. The station actually opened on 24 October 2022, well within the DCS 1.1 equivalent opening window of the second half of 2022 and on the DCS 1.2 P50 date.

Lesson: Reviewing and confirming the scope, schedule, and Test and Commissioning programme with key stakeholders, and carrying out a Quantified Schedule Risk Analysis (QSRA), allowed the delivery team to gain support from the station's workforce and contractors, and gave them an opportunity to better the P50 (50% probability) opening date rather than continually failing to achieve a best-endeavours deterministic date. Bond Street opened on 24 October 2022, beating the revised DCS 1.3 deterministic date of 14 November 2022.

Throughout the recovery, the DCS has been the route map for the programme management team, CRL Executive, Board and sponsors. By adjusting the DCS to deal with known and unknown threats, it stayed current, credible and useful for all to know how CRL was performing in achieving the target opening window. The table below describes the various iterations and reasons for change, and key milestones.

DCS version	Endorsed	Key events and reason for change
DCS 1.0	Q3 2019 CRL Board	EOP sets new delivery dates following announcement of delay. First Delivery Control Schedule to deliver EOP baselined.
DCS 1.1	Q3 2020 CRL Board	COVID-19 delay. Recovery strategy and DCS developed, routeway recovery strategy with blockades introduced, station schedule spread with respect to critical resource, opening window set for COS in first half of 2022, with nine 12-tph stations and BOS at SC2.
DCS 1.2	Q3 2021 ELDG	Entry into ROGS and Trial Running period started 26 March 2021. Adjustment to DCS 1.1 through stations sequencing and Trial Running/Trial Operations durations for emerging learning. Opening window held.
DCS 1.3	Q3 2022 ELDG	Opened COS to passenger service (12 tph) 24 May 2022, all stations except BOS. BOS schedule critically reviewed and updated. DCS ownership transferred from CPO to Elizabeth line Director, introduced Stage 5B Minus (22 tph). Achieved 6 November 2022.

Figure 6 The iterations of the DCS and drivers for change

10 Summary

Through a combination of Recovery Strategy development and refinement, organisational change to create the right environment and the creation of a robust but agile DCS, CRL and its partners were able to recover from the delay announced in 2018, deal with the impact of a once-in-a-generation global event and deliver a truly world-class railway through one of the world's busiest cities to great acclaim.

We have taken the 43 strategic insights, lessons learned and avoidable risks, and developed a matrix of 20 high-level lessons learned aligned with the DfT paper on *Lessons from Transport for the Sponsorship of Major Projects*[1] (see Appendix 3).

The five key DfT sponsorship themes from the paper are:

A – Accountability must be unambiguous

B – Behaviours matter more than process

C – Control schedule and benefits as well as cost

D – Deal with systems integration

E – Enter service cautiously

To these we have added two programme management themes:

F – Facilitate investment in leadership and team

G – Generate and maintain an agile delivery strategy that is regularly tested

While every complex programme is different, it is hoped that the themes identified – along with the highlighted strategic insights, lessons learned and identified risks – may go some way to helping future programmes prepare for both foreseeable and unforeseeable events that may impact them.

1 https://www.gov.uk/government/publications/lessons-from-transport-for-the-sponsorship-of-major-projects

Appendix 1

Summary timeline illustrating the events in each theme

Year	Qtr	Recovery strategy development & adjustment to emerging threats	Organisational development to create the right environment	Control & management through Delivery Control Schedule
2018	Q2		Sponsors informed of delay	
	Q3		Delay announced publicly	
	Q4	EOP developed	New Chair & CEO. Exec recruitment starts	
2019	Q1	Board signs off EOP	SDO office stood up. Plateau 1 (routeway) created	
	Q2			DCS 1.0 Development to reflect EOP
	Q3			DCS 1.0 Board approval
	Q4		Integrated Delivery Teams stood up	
2020	Q1	COVID-19 Safe Stop	Exec complete (CFO, CPO) gold/silver/bronze in place	
	Q2	Routeway recovery strategy CUH @ SC3ROGS		DCS 1.0 updated to reflect recovery strategy
	Q3	Dynamic Testing restarted Stations recovery strategy	Plateau 2 (stations) created Commissioner appointed	DCS 1.1 Board approval
	Q4	1st Blockade 97% productive SIDT initiated December	CRL Ltd Board stood down. CEO reports to Commissioner	
2021	Q1	FAR @ SC3ROGS Entry into TR & ROGS 26 March 2021	T-minus reviews to ROGS chaired by CPO	
	Q2	TCR/WOO @ SCROGS	T-minus reviews to Trial Ops chaired by COO	DCS 1.2 development – TR delay & stations adjustments
	Q3	LIS/PAD/WHI @ SC3ROGS		DCS 1.2 endorsed by ELDG
	Q4	Start Trial Ops P1		
2022	Q1	Start Trial Ops P2 mass evac. CAW @ SCROGS		
	Q2	Elizabeth line COS opens 24 May 2022 (Stage 3 & 4)	Plateau 1 transitions to RfLI CEO stands down	DCS 1.3 development starts, transitions to RfLI
	Q3		CRL Exec dissolved CPO reports to Commissioner	DCS 1.3 issued to reflect modified staging (22 tph)
	Q4	BOS opened 24 October 2022 Stage 5B Minus (22 tph) opens 6 November 2022	Transition to CRL close-out	
2023	Q1		CRL close-out team formally stands up. CPO stands down	
	Q2	Stage 5C (on target)	CRL delivery team disbands	

Appendix 2

De minimis requirements and structured approach to the EOP (2019)

Crossrail recognised that the following requirements could not be compromised.

- Full end-to-end railway (trains running from Abbey Wood to Paddington) operating at least 12 tph.
- An absolute minimum of five stations opened to the public including Paddington, Tottenham Court Road, Farringdon, Liverpool Street, Canary Wharf and Abbey Wood.
- A clear migration plan for subsequent full Stage 3 (stations and functionality)
- Stage 4: Great Eastern connection of services with Shenfield to be capable of opening no more than six months later.
- Stage 5: Great Western services to be fully connected into the COS no more than 12 months later.

Within Stage 3, Crossrail created tranches that split the completion, assurance, handover and operational readiness of infrastructure.

- Tranche 1: Shafts and Portals – prior to EOP, the degree of complexity of the Shafts and Portals was not fully understood in the baseline MOHS, and completion of the Shafts and Portals was linked to stations. This created a delivery risk on the programme that needed to be uncoupled.
- Tranche 2: Abbey Wood, Woolwich, Custom House and Canary Wharf.
- Tranche 3: Routeway, Paddington, Tottenham Court Road and Liverpool Street.
- Tranche 4: Farringdon and, subject to further planning, Whitechapel and Bond Street.

The completion of all four tranches made up Stage 3.

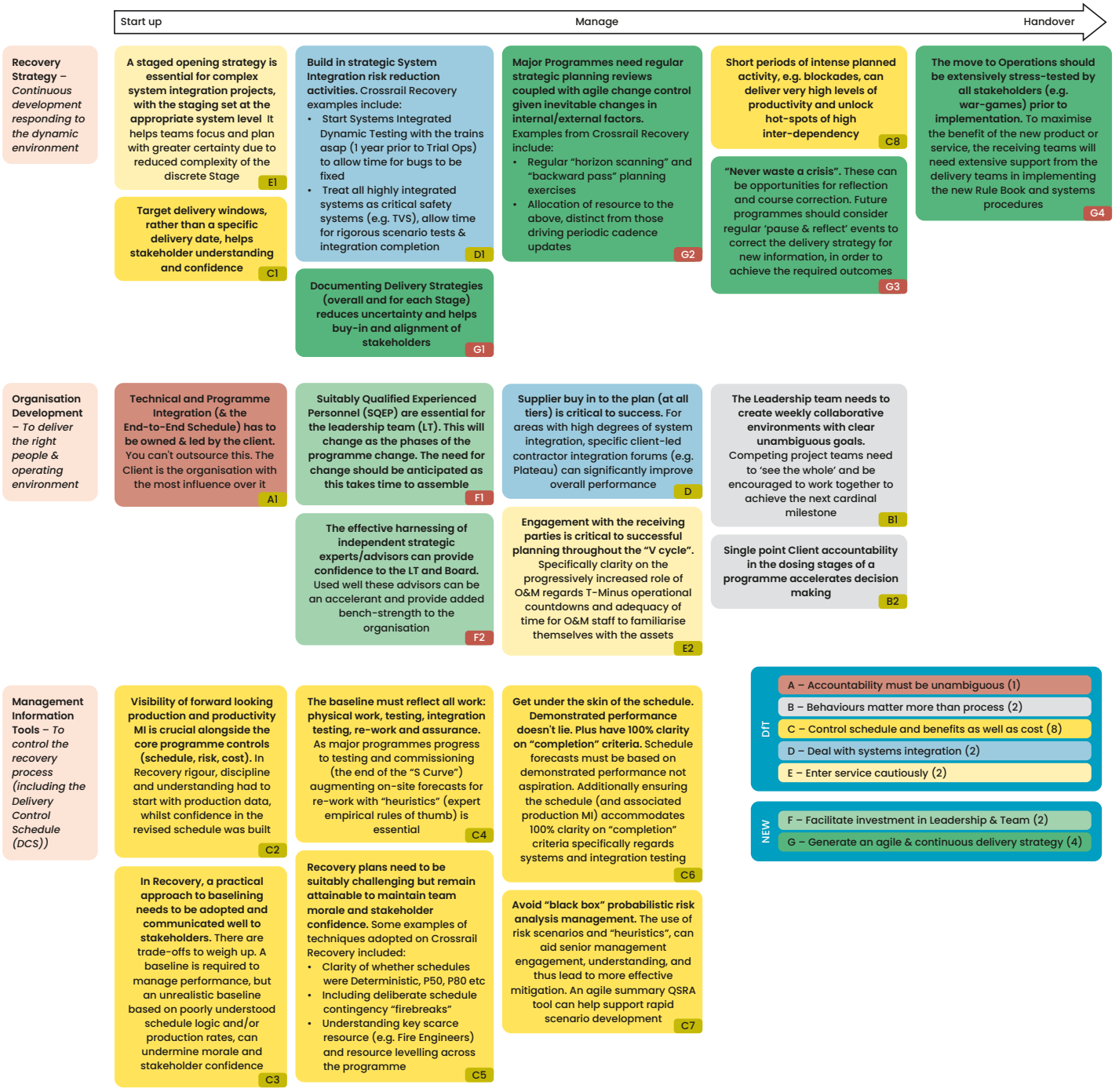
A key enabler to achieving the staged delivery and the tranches within Stage 3 was the introduction of a three-part configuration approach: asset completion, assurance and handover to operations. To do this, Crossrail introduced the concept of 'configuration-staged completion' (SC1, SC2 and SC3).

SC1 included the completion and assurance case for PSDs, platforms and signalling rooms, providing the infrastructure to support the railway and allow full-scale Trial Running. SC2 included the safety case for a station to have suitable evacuation routes. SC3 was readiness for passenger use.

This configuration-staged completion approach allowed Crossrail to plan an EOP with the option for Bond Street, Whitechapel and Farringdon stations to achieve a minimum of SC2 (available for evacuation) but not SC3 (open for passenger use) on Entry into Passenger Service.

Appendix 3

High-level lessons learned, linked to DfT paper on *Lessons from Transport for the Sponsorship of Major Projects*



Crossrail cost to complete: Cost and commercial management

1 Introduction

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In August 2018, Crossrail Ltd (CRL) announced that the programme to open the Elizabeth line would not be delivered on the original estimated timeline and that the opening of the Central Operating Section (COS) by December 2018 was not achievable. It was also made public that the original estimated budget would be insufficient and that additional funding was required to complete the programme. In late 2018, the Department for Transport announced that the central section funding would be increased to £14.9bn, a £2.15bn increase on the previous limit of funding, enabling the programme to continue with the works.

The delays led to the need to develop a new delivery strategy that could take the programme to completion. In the first half of 2019, after several months of intense planning, Crossrail announced a revised opening window reflecting the Earliest Opening Programme (EOP). The plan was to bring the central section of the line into Revenue Service as early as possible between December 2020 and March 2021, opening all stations except Whitechapel and Bond Street, which would not be complete by this date. This strategy introduced the concept of staged configurations to allow progressive completion of key testing activities. A bottom-up schedule was developed to reflect this logic called the Delivery Control Schedule (DCS 1.0).

By the start of 2020, it became evident that the timescales outlined in DCS 1.0 were not achievable, mainly because of the volume of testing, commissioning and assurance activities required to complete the programme, and the productivity levels that could be achieved in completing this work. In March 2020, the COVID-19 pandemic caused the programme to undertake a 'Safe Stop' when the national lockdown was introduced. Work resumed in the second half of April for 'niche works' – critical works that could be delivered with small teams working under social distancing rules – but Crossrail used this pause to improve its plan to deliver the remaining works. This brought further resilience to the programme that would ultimately deliver the opening of the COS.

In August 2020, a revised strategy was completed: the new plan was to bring into Revenue Service the central section, this time only excluding Bond Street, in the first half of 2022 and to complete integration of the full end-to-end railway by mid-2023. This new strategy was underpinned by an updated Delivery Control Schedule (DCS 1.1) and supported by a thorough cost and risk modelling process.

This process concluded that additional funding of up to £1.1bn was required, a value that remained valid until the end of the programme. At the time of writing, the P50 forecasted cost was £104m lower than the £1.1bn headline, and the reduction trend was expected to continue as risks and provisions were retired, due to successful delivery and commercial close-out.

This revised DCS 1.1 and the associated cost estimate supported the funding negotiations that led to an additional injection of £825m funding at the end of 2020, and £98.5m in autumn 2022, taking total CRL funding to £15,887m.

This paper explains the methodology used to determine a robust cost estimate for DCS 1.1 and the measures implemented in the closing stages of the programme to maintain control, provide agile decision making and support final close-out.

2 Implementing cost controls

Following the announcement that the programme would be delayed and would not achieve the planned opening date at the end of 2018, CRL went through a strategic planning phase that included not just the development of a revised delivery plan, but also the reinstatement of the organisation required to support the completion of the programme. This remobilisation process included the Commercial, Cost and Risk Management functions that had been largely demobilised during 2018.

At the start of 2019, there was no consistent structure for the reporting of cost forecasts from projects and a lack of risk assessments resulted in significant uncertainties associated with the potential final outturn cost of the programme. Systems used to manage cost and risk either were fully discontinued or became less relevant for control activities. All these factors resulted in the recognition that these fundamental control processes needed to be reinstated.

To address this, a cross-functional team led by the Commercial and Finance teams was created to reinstate comprehensive and consistent cost management of the programme, which was at the time spending in excess of £80m per period. In addition, the team conducted estimation activities to understand how much the programme's final cost would be. This exercise included the full reinstatement of risk management activities, cost modelling and commercial planning and, working closely with the other control functions, was responsible for providing the cost estimates (Deterministic, P50 and P80) that supported strategy developments and funding negotiations.

There were a number of challenges to providing a robust and comprehensive cost and risk estimate.

- The programme was under significant external scrutiny and an enhanced level of reporting and governance.
- There were competing priorities for the control functions to support day-to-day delivery of works and inform the EOP revised strategy and baselined plan.
- The capability, processes and tools were still being reinstated.

From the point at which the delay to the opening of the programme was announced in August 2018 until the publication of DCS 1.1, Crossrail went through a learning process that led to an increased understanding of the scope and integration required to complete, providing a better view of the challenges ahead and problems that needed to be resolved.

Throughout 2019 and the first half of 2020, a number of issues emerged that resulted in more work needing to be done to complete the programme. Problems with emerging scope, productivity and progress of assurance activities were adding further pressure to the schedule and cost.

The need to produce reliable estimates, in an agile methodology, that were aligned to the different updates of the Crossrail schedule on a periodic basis led to the development of an integrated cost and risk estimating model.

3 Modelling Crossrail's final cost

In order to bring consistency and clarity to the estimation of the Anticipated Final Cost (AFC), the Finance team developed a central cost model that could be used to inform the programme estimate, and to validate the project cost plans that were developed with individual project teams.

The model was built considering multiple factors that could impact the AFC, producing a set of overlays that were applied to each contract. Key variables included in the model are listed below.

- Programme key milestones (Trial Running, Trial Operations, Revenue Service, etc.)
- Key milestones or dates for each individual station (completion of Stages 1, 2 and 3 when applicable, handover, contract completion)
- Commercial structure of major contracts (settled sum and cost-reimbursable components)
- Crossrail workforce plan (Indirects)
- Central reserves (identified scope gaps, COVID-19-specific mitigations, management reserves, etc.)
- P50 and P80 Quantitative Cost Risk Assessment (QCRA)

The estimating methodology was applied periodically in the programme from the EOP, development of DCS 1.0 in August 2019 to DCS 1.1 in August 2020, allowing the review and validation of the cost and risk model outcomes. This process was key for the early-programme strategic planning phase, providing reliable cost information for the different decision-making processes in the programme. The model was also utilised to support ad-hoc scenario analysis providing meaningful and timely estimates.

This modelling approach provided schedule, cost and risk alignment to the programme; all estimates produced were aligned to assumptions included in the control schedule. A set of periodic instructions (dubbed as 'Riding Orders') were implemented collaboratively between the Controls, Finance and Commercial teams, and issued to projects to ensure that the bottom-up estimates were based on a common set of assumptions that made the programme modelling process robust and reliable.

To gain confidence in the outcomes of the model, a series of internal and external independent reviews were performed, including a set of third-party expert 'red and black' reviews, in which the black review was focused on cost and commercial position.

4 Setting an achievable baseline

In the first half of 2019, the EOP requirements were to produce an evidence-based strategy to bring the railway into Revenue Service as soon as possible in a safe, assurable and reliable way. The strategic planning helped Crossrail recognise the challenges associated with systems interfaces, signalling updates and asset configurations. The bottom-up schedule that reflected the EOP top-down strategic planning was called DCS 1.0.

The planned handover of shafts and portals provided an opportunity to test the assumptions built into DCS 1.0, and highlighted a number of issues with productivity and the complexity of the tasks.

Adherence to DCS 1.0 rapidly became a challenge, with the programme achieving on average 33% of planned activities each period. Complex interfaces between different projects and systems at this stage of the programme were creating challenges, impacting planned delivery dates and associated costs.

An improved level of scrutiny of the activities required to test, assure, commission and hand over each asset and the railway as a whole was implemented, including the creation of a number of configuration states. This provided a better understanding of the overall programme and associated challenges, and plans were developed to increase maturity and confidence in the strategy.

In March 2020, the COVID-19 pandemic hit the programme, a controlled Safe Stop was instructed and all activities were stopped. This provided a key opportunity for Crossrail to reassess and plan the upcoming milestones, reducing its associated risks. Productivity levels before the Safe Stop were low, overall workforce in the programme was around 4,000 full-time equivalents and progressive demobilisation was a challenge.

The Safe Stop allowed the programme to focus on assurance activities; working from home arrangements were implemented that helped to focus the efforts on the production of required assurance documentation.

In mid-April 2020, a 'niche work' approach was taken, mobilising small teams back to complete specific activities with high impact on the critical path of the programme, while complying with social distancing rules.

A COVID-19 Recovery Strategy was developed that incorporated specific interventions to support the remaining works. Key components of this recovery strategy included bench agreements with the supply chain to allow identified critical resources to remain available for the programme as Safe Stop and niche working arrangements were implemented, and the introduction of construction blockades, with a significant positive impact on productivity.

The schedule implications of this recovery strategy were incorporated into a revised DCS and an update produced called DCS 1.1.

This was the key turning point for cost management in the programme, as DCS 1.1 and the aligned cost estimate provided a robust strategy to achieve completion, incorporating all lessons learned from DCS 1.0 in areas such as remaining physical works, the amount of testing and assurance required, and revised productivity assumptions.

5 Developing a robust cost estimate

The DCS 1.1 AFC estimate provided a range for the potential final cost of the programme, including a P80 upper band that forecasted that up to £1.1bn of additional funding would be required. This estimate remained valid for subsequent DCS updates (DCS 1.2 and 1.3) throughout the remaining duration of the programme and supported the negotiations of funding agreements with the sponsors.

The key building blocks of the estimate were:

- base cost (cost estimates submitted by project teams for deterministic schedules)
- management reserves/overlays
- project and programme risk (including prolongation)

The 'cost to go' comprised significant levels of management reserves and risks for a programme in its closing stages (comprising approximately 53% of cost to go), which represented the historic experience of the programme to date and recognised the challenges that were ahead. Risk and provisions were estimated utilising an evidence-based approach, including detailed assessment of potential commercial issues for each of the main contracts, scope gap analysis and potential additional COVID-19 pandemic impacts (for example, the potential additional impact of social distancing measures). The programme team benefited from the significant level of consideration and supporting analysis that was put into producing the final DCS 1.1 estimate.

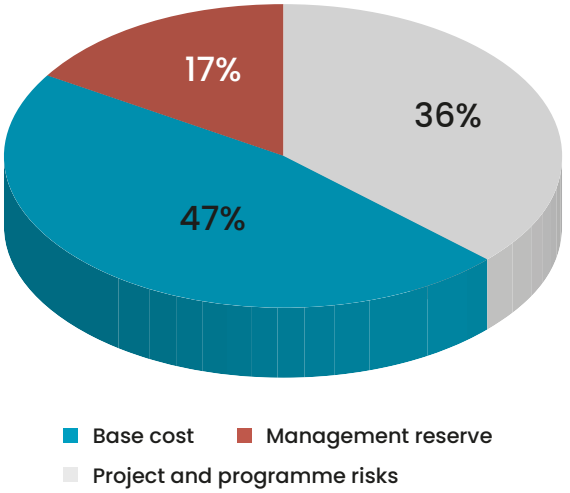


Figure 1 P80 DCS 1.1 cost-to-go building blocks

The DCS 1.1 AFC estimate was subject to internal and external assurance reviews. Detailed analyses of the methodology utilised and outputs produced were performed to increase the confidence on it. Internal assurance reviews led by senior executive members of the programme, project representative reviews and sponsor-instructed independent reviews were done as part of the validation process.

The AFC estimate was produced considering:

- alignment between cost, risk and schedule via implementation of programme overlays based on project-specific periodic run rates
- supply chain estimates
- provision for issues managed at programme level (i.e. COVID-19-specific mitigations, scope gap, commercial allowances, etc.)

In parallel, and as the delivery strategy was developed, a restructured governance cycle and meeting cadence was introduced across the programme, including three levels of review at the project, programme and senior executive levels before reporting to the Crossrail Board or Transport for London (TfL) Elizabeth Line Delivery Group (ELDG; from last quarter 2020). This increased transparency and allowed detailed challenge of the management information and the development of interventions when required.

This revised cadence was key to programme delivery and provided a strong platform for cost and risk management activities.

6 Reinstatement of risk management

Reinstatement of risk management was a key recommendation of a third-party independent report on Crossrail in January 2019.

In early 2019, risk management capability was reintroduced into the Finance function. The primary objective of this intervention was to work with project teams to understand the levels of uncertainty and risk remaining on the main stations and railway system projects, and to include allowances for the potential impact of these risks in the cost forecasts.

A process was introduced to support project teams in the active identification, assessment and mitigation of threats to schedule and cost, and to periodically conduct QCRAs to inform reporting of projects AFC.

In addition to this, a series of programme-wide cost and schedule risk assessments were conducted to support the development of the EOP and the following DCS updates, in order to inform the likely range of outturn cost and confidence in delivering the programme within agreed funding limits.

Schedule risk analysis conducted on the delivery plan informed decision making around the prioritisation and phasing of key activities – particularly sequencing and overlap of station commissioning – to mitigate the impact of uncertainty and risk on key milestones. The risk review process was embedded on the periodic reporting cadence of the programme and the outcomes were included as key inputs to the cost and schedule review process.

The reinstated risk management process included the identification of a set of key programme-level risks to ensure full visibility of the main threats to the programme at each stage of delivery. Ownership of each of these key programme-level risks was allocated to the Crossrail Executive to allow their management and mitigate the potential impact.

Additionally, an exercise was conducted to identify and map the enterprise risks held by Crossrail and its partner organisations. This exercise informed discussions on transition of the railway and key capabilities within the programme team required in the operational organisation.

7 Managing the programme AFC

Following the development of the DCS 1.1 AFC estimate, a strong and consistent cost and risk management process was implemented. This process was supported by the restructured periodic cadence and was fundamental to ensure the estimated forecast of up to £1.1bn remained valid until completion of the programme, including DCS 1.2 and DCS 1.3.

The cost and risk management process was embedded in the periodic review cycle and included key steps to allow the identification, review and management of emerging cost pressures reported by projects. These pressures were assessed against identified management reserves or risk provisions, providing stability to the programme AFC and allowing the programme to periodically evaluate the remaining risk exposures and associated cost implications.

The collaborative approach between the programme and projects – particularly (but not exclusively) regarding cost, commercial and risk areas – led to further strengthening of the cost management activities. Channels of communication were implemented, and challenges were addressed and resolved with a problem-solving approach. This increased the transparency of the reported information and generated a dynamic and agile environment critical for management activities.

A revised AFC baseline was set across the programme based on the DCS 1.1 estimate and projects were measured against it. Deviations were reviewed and challenged on a periodic basis, and project managers were accountable for the correct control and management of this revised baseline.

A cost-control culture was embedded in the organisation: from executive members to project teams, the whole programme was focused on managing the AFC. An enhanced and agile change control process was implemented ensuring that all required changes to the baseline were reviewed by all involved parties.

This revised change process included the development and implementation of a new change form, which was critical for the success of the process. The form required approval from relevant areas in the programme and included detail about the following main aspects for the change to be approved: cost and schedule impact, change overview, commercial implications, options analysis, benefits and operator/maintainer implications.

The change process also benefited from the change in programme governance when the programme moved into TfL and began to report directly to the ELDG, led by the TfL Commissioner. This move facilitated a rapid decision-making process, allowing the programme to raise and resolve changes within an average of 10 days.

7.1 Quantitative risk assessment

The programme team maintained a comprehensive risk management process across the delivery and supporting functions. This included periodic review of risks facing each project team, focusing on the key threats to cost and schedule.

All projects managed risks relating to their objectives and maintained their own risk registers with support from a specialist team of risk managers. On a periodic basis, each project presented an updated QCRA that formed part of the project AFC and was scrutinised in the periodic review. In this review, cost impacts were analysed, mitigation actions were challenged, and any wider implications to other projects and the programme were identified. Schedule risks were included in the programme-wide QSRA (Quantitative Schedule Risk Assessment).

The key functions – including Technical, Assurance and Operations – also maintained active risk registers supported by the central risk team. The scope of these registers was those risks outside of the projects' control or those best managed at programme level. Functional risk management performance was a key focus of the periodic review process and these risks informed a programme-level QCRA, which formed part of the programme AFC.

Based on risk information provided by project and functional teams, the central Risk team produced a periodic QSRA that assessed the confidence level of achieving key programme milestones and informed an assessment of potential prolongation costs. In addition, this assessment indicated the key risks to be managed at each stage of the programme and informed the critical areas requiring intervention by the programme leadership team.

Following the creation of a robust baseline at DCS 1.1, the pace of the programme increased with good progress being made on a number of fronts. This resulted in a significant volume of movement in the risks being faced, both in terms of risks impacting and being mitigated. The periodic update of the risk profile proved to be a dynamic activity that required good communication and integration between the Cost and Risk Management teams.

Programme risks and provisions were centrally controlled, and the revised change control process was utilised to allow projects to draw down from them, ensuring detailed review and challenge of all suggested changes.

Example: Management of programme risks – impacts of social distancing during the pandemic
DCS 1.1 was produced in summer 2020 and made a number of assumptions about the social distancing requirement and the impacts on contractor productivity. All projects were instructed to exclude risks associated with the uncertain outlook once that initial period had expired. As the rules continued to be updated through the remainder of 2020 and into 2021, all impacts related to social distancing and the impact on productivity were managed centrally as a programme risk, avoiding double counts and providing transparency regarding the cost and risk implications.

The evolution of the cost to go, from when DCS 1.1 was developed to Revenue Service, provide a view of how risks and management reserve were controlled. As issues materialised or were mitigated, provisions were either transferred into base cost or released, changing the proportions between the cost to go components.

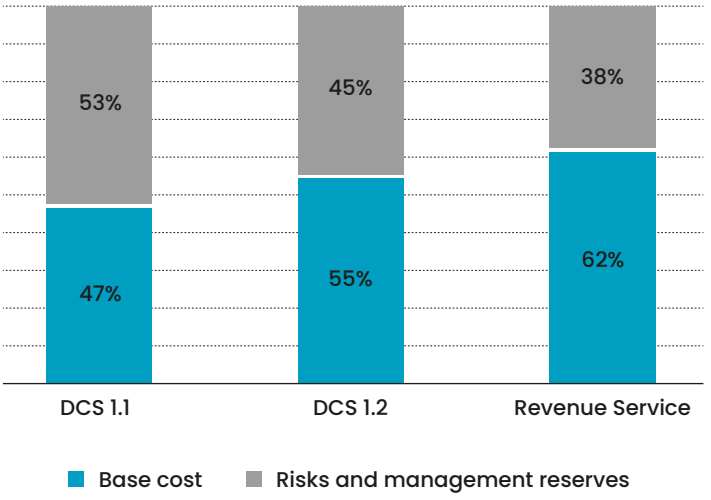


Figure 2 Evolution of P80 cost-to-go building blocks

8 Key governance meetings

A three-stage periodic review cycle before reporting to the CRL Board or, subsequently, to the ELDG was implemented in the programme.

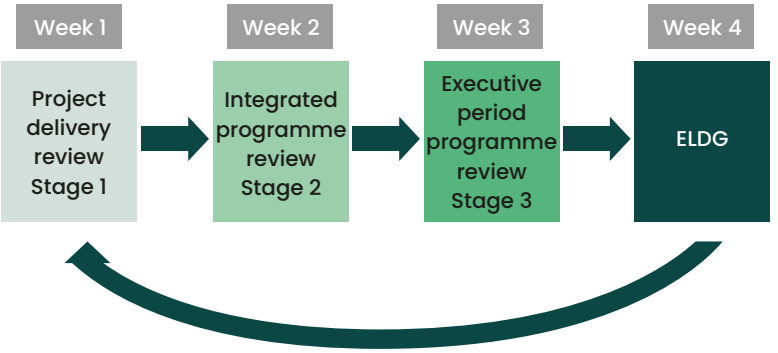


Figure 3 Periodic review cycle from the second half of 2020

Relevant and timely information was reported from projects to programme and programme to executive level to support the baseline management activities.

This review process ensured information was reviewed within four weeks of the period cut-off, starting in week 1 with project reviews at contract level, followed by consolidated project and programme review in week 2, CRL executives signing off period performance and overall schedule and AFC position in week 3, then presentation to the Board or subsequently the ELDG.

8.1 Stage 1: project delivery reviews

Project managers reported the performance of each individual key project in each period to programme level. This included safety, delivery successes, issues, schedule and projects AFC.

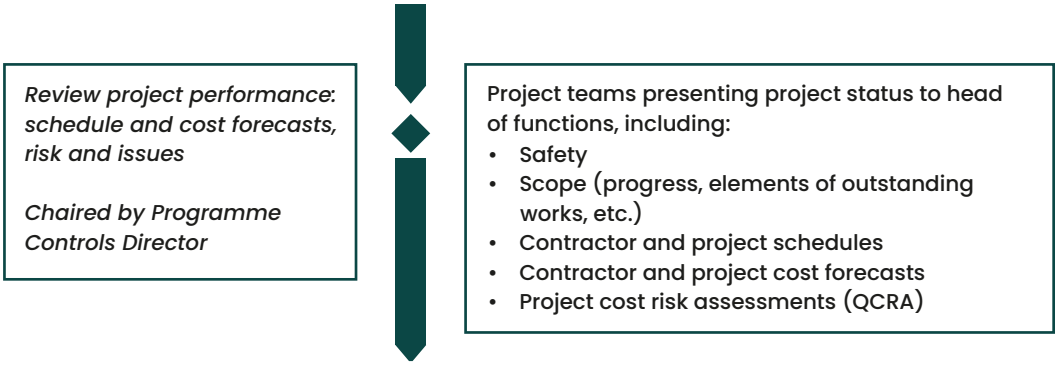


Figure 4 Project delivery review

Following project delivery review, the programme Cost and Risk Management teams performed a set of activities to integrate and assess the impact of reported project positions. These activities included the following:

- analysis of projects' cost movements, including approved changes and forecasted increases
- identification of cost movements and associated offset from management reserves or risk provisions
- updating the programme schedule and cost risk assessment (QSRA/QCRA)
- consolidation of the programme AFC position
- identifying strategies to address residual cost movements

8.2 Stage 2: integrated programme review

Integrated programme information was presented by sector delivery directors or senior project managers to the Chief Programme Officer and Chief Financial Officer (CFO).

The Finance and Programme Control functions also reported consolidated period positions.

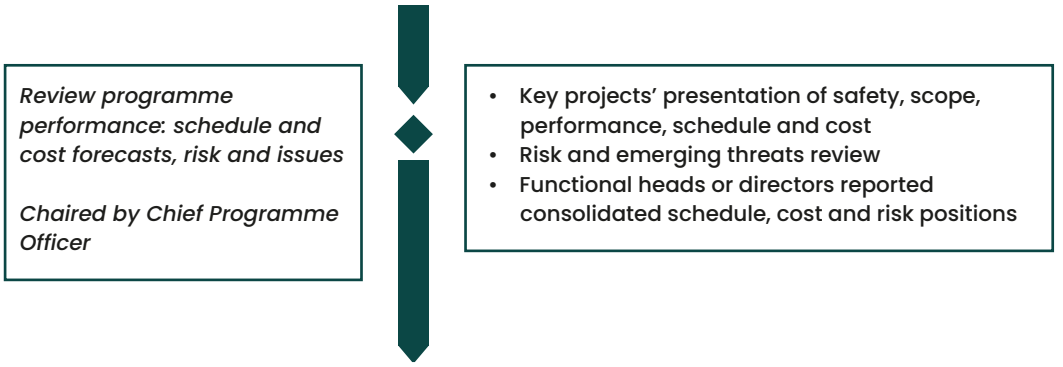


Figure 5 Integrated programme review

Integrated programme review provided further focus on cost and risk management activities, allowed the early identification of risks and emerging threats, and supported the development of programme interventions to mitigate their impacts.

It was a key forum to ensure the timely and direct reporting of period performance to the Chief Programme Officer, increasing transparency and incentivising a forward-looking approach to management activities.

- How have we performed in the period?
- How does this performance impact our plans?
- Are cost, risk and schedule aligned?
- Are we reporting a consistent view of the programme?
- What needs to be done to ensure we continue on track to deliver our key milestones?
- What are our risks and emerging threats?
- What are we going to do to mitigate them?
- Are management interventions needed?
- Who will deal with issues and when (accountability)?

8.3 Stage 3: Executive periodic programme review

The Executive periodic programme review was in place until Revenue Service and was then replaced by a programme finance review chaired by the CFO.

Figure 6 Executive periodic programme review

The periodic cadence was built to ensure that the senior management team on the programme was receiving accurate information in time to allow challenge and interventions. This dynamism and transparency was fundamental to support robust cost management and control activities. The whole programme, from projects all the way up to the Executive team, was aware of and actively managing the challenges that were emerging.

The final step on the periodic cadence was the presentation of the consolidated programme position to TfL's Elizabeth Line Delivery Group (ELDG), which replaced the Crossrail Board in the last quarter of 2020 and provided a new governance framework for the programme.

Figure 7 Presentation to the ELDG

9 Internal assurance reviews, enhanced control

Off-cycle internal assurance reviews were performed to provide further scrutiny and challenge to projects' AFC. The reviews were led by the Finance and Commercial teams and covered the following areas:

- Alignment to schedule
- Alignment to supply chain estimates
- Estimating methodology
- Resource levels
- Commercial issues
- Emerging risks and pressures
- Accruals

Reviews were performed utilising a collaborative approach; the aim was to increase confidence in the reported numbers. Identified issues were addressed and mitigation plans developed between project and programme teams.

Workshops with a focus on cost to go were also implemented to support cost reduction activities. Led by the CFO, detailed reviews of all cost to go components were performed and opportunities identified. Actions to materialise these opportunities were agreed between executive members and project teams, and reductions in project forecasted costs were reported as these opportunities crystallised.

10 Workforce planning and management cost control (Indirects)

Following remobilisation in early 2019, it was critical for the programme to ensure that the appropriate capabilities to support the delivery of the remaining activities could be secured. Crossrail resources and related costs were managed as one 'major contract', and reported in the management information materials as 'Crossrail Indirects'. These included staff (resources) and non-staff (IT, office space, insurance, audits, etc.) costs.

As the nature of the work being undertaken focused on client-led activities such as testing, commissioning, assurance and handover, the proportion of indirect versus direct spend increased.

Crossrail Indirects rapidly became a critical area of the programme and interventions were developed not just to secure the required resources, but also to manage an evolving and significant component of the programme AFC.

By the end of 2019, cost to go of Indirects represented approximately 20% of the total base cost (before risk and management reserves), a percentage that increased to more than 25% after the DCS 1.1 estimate was developed.

In addition, there was a clear relationship between evolving schedules and required extensions to people's end dates, which generated significant movement of resources planned to undergo demobilisation. There was a strong need to stabilise cost movements of Indirects to ensure that:

- the cost of Indirects was optimised and the best viable option utilised to fill positions
- individuals knew the plan and had as much certainty as possible of expected demobilisation dates
- there was increased certainty of the cost of Indirects
- uncertainty on remaining durations was appropriately managed and provisioned for

To achieve these, two processes were put in place.

- Costs of Indirects were baselined after each DCS update or at a key stage of the programme. A workforce plan was produced, underpinned by key milestones linked to capabilities and resources, to ensure that all requirements were covered. Updating the baseline in this way reduced the number of ad-hoc extensions and increased the stability of Indirects costs. This also enabled the programme to communicate expected end dates to the teams and individuals involved.
- A review panel was chaired by Crossrail's CEO, to review all resource requirements and challenge extensions. Responsible directors had to provide detailed justifications for any movement, explaining not just the change to dates but also the best mechanism to get the resources required, factoring in technical capabilities, cost and the urgency of the request. The panel included representation from the different delivery and operations areas of the programme, Finance and Human Resources.

The implementation of these interventions had a positive impact on the management of Indirects, reducing uncertainty regarding people's end dates and stabilising cost pressure.

11 Commercial strategy and its impact on the programme

As Crossrail emerged from the strategic planning phase in the second half of 2020 and DCS 1.1 was completed, it was clear that a robust and structured commercial strategy was needed to support the final completion of the programme. Existing commercial arrangements were not designed to incentivise final completion and demobilisation of Tier 1 contractors from the site. The combination of settled-sum milestones plus reimbursable cost did not provide the programme with enough tools to support required delivery activities, and was generating the prolongation of high periodic costs (run rates).

Up until this point, Crossrail had tried different commercial mechanisms to incentivise the supply chain to work in an integrated way towards the delivery of key milestones to unlock final completion. Common incentives were implemented under the name of the Common Incentives Framework but did not provide the desired outcome.

Crossrail recognised that due to the level of completion and complexity of the remaining works, the integration risk should be owned by the programme. This led to the implementation of a non-contractual environment with suppliers to integrate the remaining activities from a technical and schedule perspective. Two teams, led by Crossrail, were created: Plateau 1 was responsible for the integration of routeway and systems, and Plateau 2 for station commissioning. This was a key decision that simplified the relationship with the supply chain and supported the completion of remaining activities.

Following the successful implementation of the Plateau teams, a commercial strategy was developed with a focus on completion of the remaining works, demobilisation and final account/contract completion of all major contracts.

The strategy included the introduction of an Alternative Delivery Model (ADM) for scope where more effective and efficient ways of delivery could be identified (i.e. utilising existing TfL teams as a delivery mechanism), and provided a path for final completion and site demobilisation of Tier 1 contractors. This strategy was underpinned by DCS 1.1 and the associated cost estimate, and was used to incentivise the delivery of key milestones relevant to the programme in the integrated schedule.

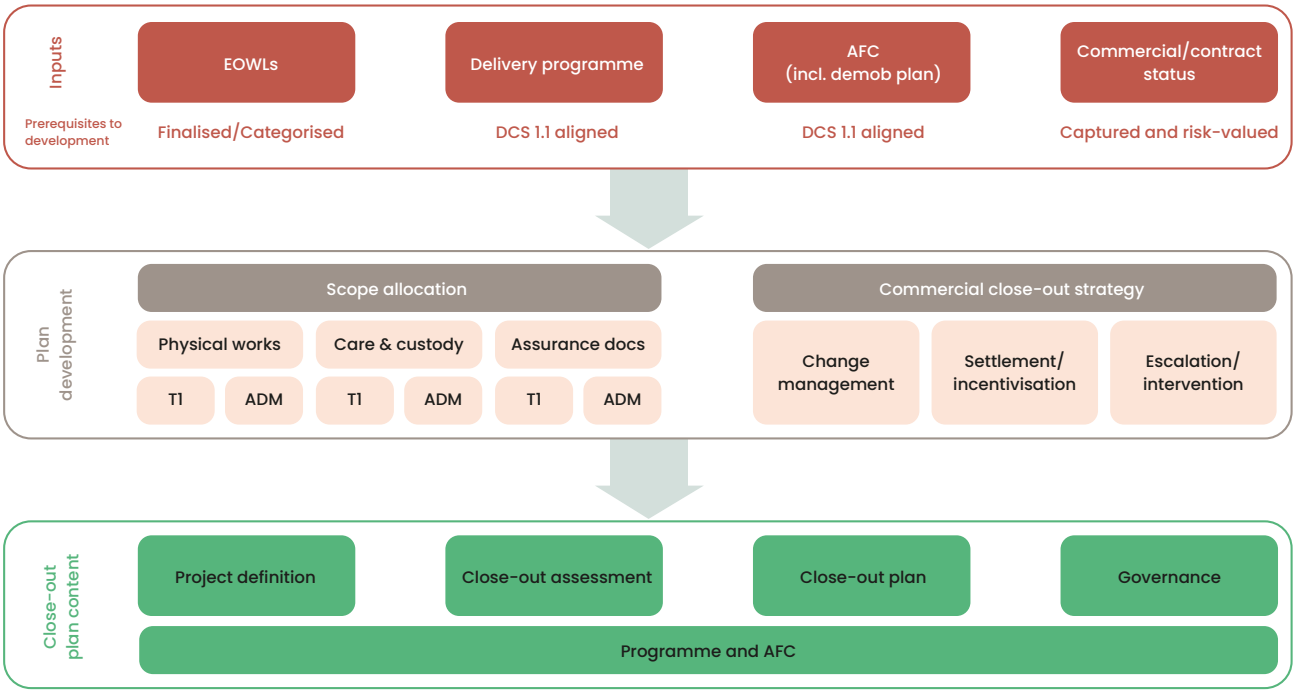


Figure 8 Commercial strategy structure

The commercial strategy included a detailed analysis of the different aspects of the projects. A plan was developed for each major Tier 1 contract that was used to analyse the required interventions to ensure successful implementation. The plan included the following.

- *Project definition*: Overview of the status of the scope, commercial, schedule, risks and performance of the different projects. These provided the data and baseline against which the close-out structures and mechanisms were selected.
- *Close-out assessment*: Review of best close-out mechanism for each individual major contract, including measures of incentive and budgets.
- *Close-out plan*: Definition of the proposed scope delivery model, any required contract changes, benefits, programme certainty, delivery assurance and supplier positioning.
- *Governance*: Lists of the required approvals to implement the various aspects of the close-out plan, including targeted dates for presentation of papers.
- *Close-out programme*: Milestone schedule of the engagements, interventions, meetings, change papers and negotiations required to deliver the project close-out.
- *Opportunities*: Details of any other potential areas of betterment across the AFC or programme that could be driven by the project team beyond the finalisation of the project close-out plan, including key actions and owners for the opportunities.

To ensure the effective implementation of this strategy, three enabling mechanisms were identified.

11.1 Micro-incentivisation of contractors to achieve key programme dates

Specific incentives were agreed with Tier 1 contractors to support the achievement of key programme milestones for specific projects.

Bespoke incentives for each project were developed and assessed against programme-level provisions to ensure they were not generating additional cost pressures. This provided the programme with a mechanism to drive Tier 1 contractor performance and demobilisation from the site.

11.2 Demobilisation of Tier 1 contractors

Demobilisation of the supply chain from the site was critical to support programme cost control. Prolonged periodic run rates were building pressure on the programme's estimated AFC and mitigations were needed to avoid further cost escalation.

Several interventions aiming to demobilise Tier 1 contractors were made, but limited success was achieved. This was driven by:

- the continued identification of new scope
- required work as the result of assurance/quality issues
- historic commercial agreements in place that did not incentivise demobilisation
- the absence of a clear path to overcome close-out issues such as residual works completion (documentation and physical works)

The implementation of an Alternative Delivery Model for residual works plus the introduction of the previously mentioned micro-incentives provided the right platform, which supported demobilisation of Tier 1 contractors. Target dates for completion of 'must' works to be delivered by the supply chain were defined and projects measured against them.

All target demobilisation dates were achieved within the negotiated ranges and station Tier 1 contractors were successfully demobilised as planned.

11.3 Final account and contract completion

Thirty-six main Tier 1 contractors were identified in the programme including those involved in tunnelling, stations, shafts, portals, power, signalling, communications and control, and track contracts.

Strong management capabilities within the Commercial team were fundamental to drive success in this area. Bringing in the right skills for the close-out phase of the programme was essential to the achievement of the expected outcomes.

The Crossrail Employers' Completion Process (ECP), and the management of it, was also crucial in driving success with the final close-out of the programme. A detailed list of activities with progress indicators against each of them was used to drive completion of each of the main contracts.

Supported by the commercial close-out strategy and final account agreements at the time of writing, the programme has achieved commercial close-out for 22 of the main Tier 1 contracts and 11 are in the defects period or have ECP signed off.

12 Conclusions and lessons learned

After remobilising in early 2019, Crossrail experienced a series of delays and emerging issues that resulted in increases to the estimated outturn cost. The implementation of a robust cost and risk estimation and management process was fundamental to support the final phase of the programme.

In this paper, we have described the main interventions implemented by the programme to regain control over the AFC and how the close-out commercial strategy supported this process.

Although some of the challenges faced by this programme were no doubt specific to Crossrail, there are a number of conclusions that are relevant for the closing stages of any major programme.

The main lessons learned are summarised below. These have been classified into four themes that underpin the cost, risk and commercial management processes in the programme.

- Controls
- Governance
- Supply chain
- Culture

12.1 Controls

The controls environment that is implemented in the closing stages of a major programme such as Crossrail needs to take the following into account:

- The complex nature of activities involved in testing, commissioning, assurance and handover.
- The reducing involvement of all parties in discrete, independent activities and increasing involvement in integrated activities that support key programme milestones.
- The nature and extent of supply chain organisations that remain in place to deliver these activities.
- The risk of reducing levels of resources in management and control roles within the client organisation, and streamlining of the systems that have been in place through the volume delivery phase.

As a result, the key learnings are:

1. Implement an integrated programme cost and risk model

An integrated model of cost and risk, to inform strategic decisions made by management and support 'what if' or ad-hoc scenario planning, is fundamental to ensure full visibility of implications. This needs to be managed at programme level and integrated with the programme schedule.

The model needs to include 'bottom-up' project estimates and allow the assessment and challenge of forecasts based on specific cost drivers.

Crossrail benefited from a cost model that considered each main contract's specific commercial structure, allowing the integration and inclusion of management overlays to ensure alignment with programme strategies.

Figure 9 provides an example of output for one specific project. The model allowed the review and analysis of emerging cost, the impact of overlays and project-specific risks. It also included key dates to ensure that forecasts were aligned with them.

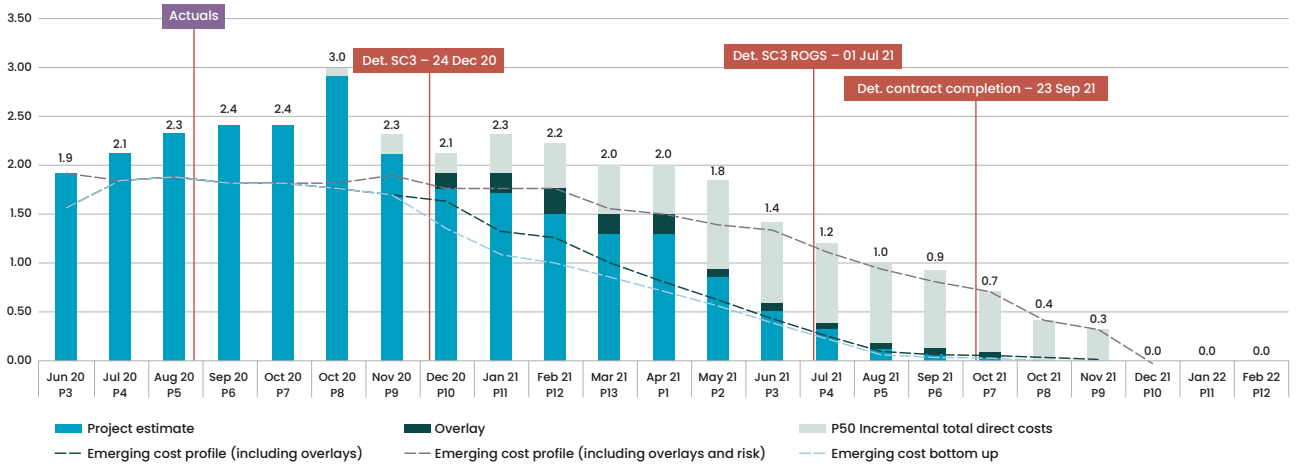


Figure 9 Example cost-to-go model output

2. Schedule, cost and risk alignment should support the periodic decision-making process

This was fundamental to keep the programme AFC under control. Assessment against defined milestones and the risks associated with them provided a strong basis for cost-estimating and management activities. This resulted in tight control of the forecasted cost.

3. Align projects with programme-level assumptions

To minimise the risk of different assumptions being applied by different parts of the organisation, information should cascade down to projects in a consistent and clear way.

When Crossrail was going through intense strategic planning, common key assumptions at project level were fundamental to ensure reported information was consistent and reliable. Crossrail implemented periodic 'Riding Instructions' to provide clarity to projects regarding programme assumptions and key milestone dates.

Standardising reported data at project level was critical to allow integration of information at programme level and support the implementation of enhanced governance.

4. Utilise the risk management process to support decision making

Integrate risk into programme cost and schedule control processes, perform periodic risk assessments and quantify emerging risks.

Actively manage the project and programme risks, and develop and implement mitigation plans and interventions to minimise exposure. Ensuring that provisions (time and cost) are included in project costs and schedules is key.

5. Cost control of Indirects must always be a priority

As a programme reaches its closing stages, the proportion of management (i.e. Indirects) costs versus delivery (i.e. Directs) costs necessarily increases. It is important that a clear workforce planning process and associated cost controls are put in in place from an early stage. For a long time, Indirects in Crossrail were one of the largest 'projects' in terms of cost to go.

The capabilities required to deliver each phase of the programme should be assessed to ensure alignment between resources and strategies.

12.2 Governance

Governance needs to recognise the increased scrutiny on a major programme in the closing stages, especially if – like Crossrail – the programme is experiencing cost and schedule pressures. There is a need for efficient reporting to enable the timely flow of management information and agile decision making that can respond to emerging issues.

As a result, the key learnings are:

1. Implement a rapid decision-making process for change control to reduce the risk of taking decisions based on non-relevant information

When Crossrail implemented the revised change control process and transitioned into TfL governance, changes were resolved (approved or rejected) very quickly. This allowed the programme to have relevant and up-to-date management information, which was fundamental to ensure agile decisions were made to unlock issues and progress towards final completion.

2. Ensure robust and structured cadence to review management information

Projects should be accountable for reported data, and periodic reviews should be held to explain progress and deviations from plans.

Schedule, cost and risk should be at the heart of the periodic reviews, information should flow from project to programme levels and an integrated view should be analysed periodically, allowing interventions if required. Timely and accurate data is fundamental.

12.3 Supply chain

Commercial strategy in the closing stages has very specific objectives: to incentivise the delivery of remaining activities, agree final account positions with suppliers and other partners, and finalise the programme's financial position. However, to achieve this on a programme of this scale and complexity, the commercial strategy needs to acknowledge the motivations and drivers of the supply chain, and the increased levels of integration and collaboration required to complete the programme.

As a result, the key learnings are:

1. Commercial strategy should ensure the programme remains in control of its own destiny

Removing leverages too early could result in cost escalation and poor performance.

Close-out strategies should incentivise the demobilisation of Tier 1 contractors, providing tools and mechanisms for it to happen. At the end of major programmes, emerging scope, testing and assurance activities will result in 'client-driven' changes to contracts that will undermine the programme's ability to drive completion.

2. Utilise the benefits of micro-incentives in the close-out stage

Bespoke incentives, developed to drive the supply chain to deliver results, based on what is relevant for the programme at each stage is a powerful tool that can be used to improve performance.

The implementation of targeted incentives associated with key milestones for the programme was fundamental to support the final completion and demobilisation of the main Tier 1 contractors. Micro-incentives allowed projects to be in control of their own destiny, and this resulted in an increased rate of milestone achievement.

3. Drive the contracts close-out process from early stages in the programme

All contracts need to be closed at some point, and the programme should ensure any commercial issues are managed in a timely manner and cost verified based on defined cost in the contract.

Look for indicators of potential issues and implement interventions in a timely manner. Accruals, cash flow, purchase orders, resource rates can indicate incubating problems; do not omit them – it is better to act and resolve.

4. Implement a structured ECP

A structured process to support final completion of each major contract is fundamental to ensure a clean close-out process. Key indicators against each element should be set to allow progress measurement. This will provide full visibility regarding the status of each project and will enable project–programme collaboration.

5. Engage with supply chain senior leaders

The supply chain needs to be informed of and aligned with the programme strategy. This is especially important in the latter phases of a project with significant systems integration to be delivered.

Rebuilding and enhancing engagement was fundamental in the final stage of the programme, opening fluid communication channels, enabling collaboration and supporting the delivery of common objectives to achieve final completion.

12.4 Culture

The closing stages of a major programme are characterised by a number of competing pressures to deliver the outcomes and benefits, often against significant challenges and under intense scrutiny.

From the perspective of cost and risk management, it is important that the culture of the organisation supports continued focus on transparency and collaboration.

As a result, the key learnings are:

1. Use internal and external (independent) assurance reviews to gain confidence in methodology, and outcomes of cost and risk information

Assurance reviews provide the space and time to reflect on the processes and results of periodic information. They should be taken as an opportunity for improvement, and work should be done in a collaborative and transparent way to take the most out of each of them.

The Crossrail AFC was constantly under scrutiny; external independent assurance reviews helped the programme to provide confidence to key stakeholders, while internal reviews helped to build trust between teams, drive cost efficiencies and improve the quality of the data.

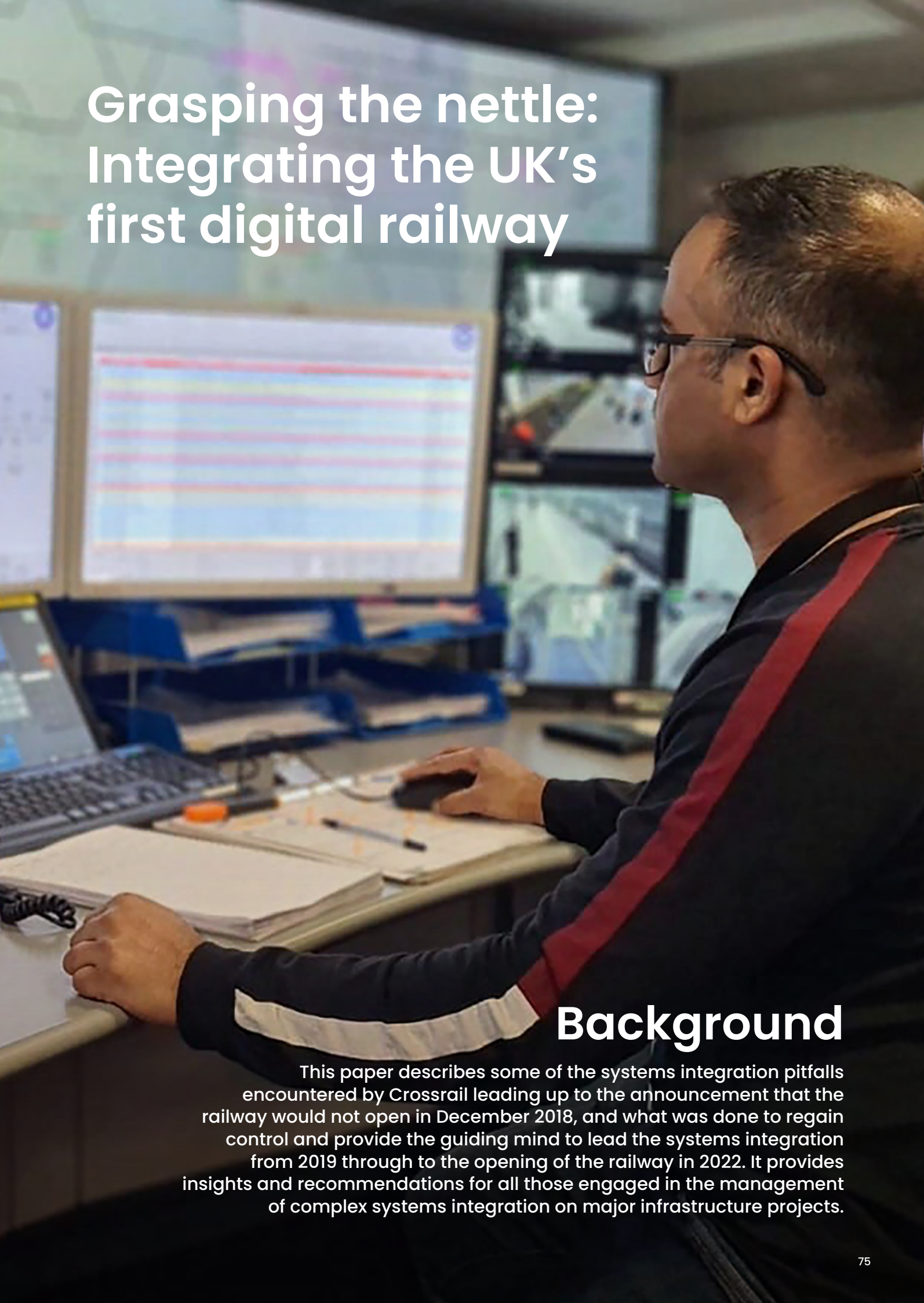
2. In programmes under stress, relationships are key to improve the outcomes

The collaborative approach taken by Crossrail to face its challenges was fundamental to its building of an achievable AFC estimate.

The commitment of projects to report realistic and transparent data helped the programme with the assessment of exposures. Pressures were reported as they emerged, allowing interventions or mitigations to be implemented. The open channels of communication allowed the programme to anticipate potential cost pressures and build in the baseline provisions required to manage them.

This was also supported by key strategic organisational changes: the Commercial team reporting line was changed to the CFO, while the Commercial Director and Commercial team remained embedded with the delivery teams. This shared-ownership model was a key part of the alignment achieved and fundamental to the implementation of interventions that proved critical to enabling final completion (for example, the implementation of an Alternative Delivery Model).

Grasping the nettle: Integrating the UK's first digital railway



Background

This paper describes some of the systems integration pitfalls encountered by Crossrail leading up to the announcement that the railway would not open in December 2018, and what was done to regain control and provide the guiding mind to lead the systems integration from 2019 through to the opening of the railway in 2022. It provides insights and recommendations for all those engaged in the management of complex systems integration on major infrastructure projects.

1 Introduction

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Technical Director, Crossrail, 2018–2022

On 22 July 2008, the Crossrail Act received Royal Assent, and earlier that same year Apple released its first smartphone, the iPhone 2G. Digital infrastructure was now beginning to fundamentally change how we communicated and controlled our lives, and infrastructure projects were starting to consider how much of this new technology they should embrace to deliver smarter outcomes. This fortuitous timing provided Crossrail with the opportunity to consider doing what had never been done before: to implement the UK's first fully 'digital railway'.

Digital technology now offers railway infrastructure owners new ways to manage and control their assets. Railways are expensive to own and operate, and most of the running costs are dictated by layers of legacy technology and inefficient operating rules. Maximising digital technology for a new railway allows outdated working practices to be overhauled and significant savings to be achieved in the full-life operating costs of the network. Crossrail worked hard from the outset to maximise these savings.

For example, Crossrail has a fully integrated Railway Control Centre (RCC), merging signalling, electrical control, tunnel systems and security systems all into a single control room. Most railways are still working on bringing their separate legacy operating systems under one roof.

Crossrail has also achieved the world's first fusion of modern mainline and metro signalling systems onto a single train: ETCS (European Train Control System) and CBTC (Communication-Based Train Control). Complex automated functions such as 'Auto-Reverse' have also been incorporated, allowing the trains to reconfigure themselves automatically and without a driver present at the end of the line. Furthermore, it has the UK's first full-height platform screen doors throughout the tunnel section, totally transforming the underground station platform environment.

Crossrail also has a modern traction power system with automatic switching and earthing capabilities, allowing fast and safe remote isolation of the overhead line. It is also one of the first railways to use a handheld possession management tablet, used by maintenance staff to block the line and safely access the track. Together, these systems have significant safety benefits to lineside workers while also maximising precious maintenance time.

As you would expect with any modern digital system, Crossrail relies on a vast dedicated communications network, allowing everything to be monitored and joined together to automate the railway; for example, when a door is opened, lights can be illuminated and CCTV can be activated. Every system, even down to the lighting in each station, is part of the network and is computer-controlled. However, with increased connectivity, the effort needed to integrate and validate a system also increases. One of the causes of the delay to the opening date announced in 2018 was the challenge of integrating such a complex and interconnected system. Crossrail aimed high when building the UK's most digitally enabled railway but inadvertently ended up with the challenge of integrating the UK's most complex railway to date.

This paper outlines some of the prominent challenges of complex systems integration encountered by Crossrail, and what steps were taken to successfully integrate and open the Elizabeth line to passengers in May 2022.

2 Complexity

Typically, major projects are risk-averse and reluctant to be burdened by avoidable uncertainty and complexity, but with a 10-year horizon, Crossrail embraced every opportunity to incorporate the latest technology into the final design. The level of ambition and the appetite for innovation were impressive, and the Crossrail team did an excellent job translating this ambition into a solid set of requirements and then into a system design. Between 2011 and 2014, everything was successfully decomposed into nine railway sub-systems across more than 30 construction elements, which were then progressively contracted out to over 10 'Tier 1' suppliers. Figure 1 shows the full extent of the works, which also included the preparatory 'On-Network Works' (ONW) carried out by Network Rail to prepare the existing lines for Crossrail.

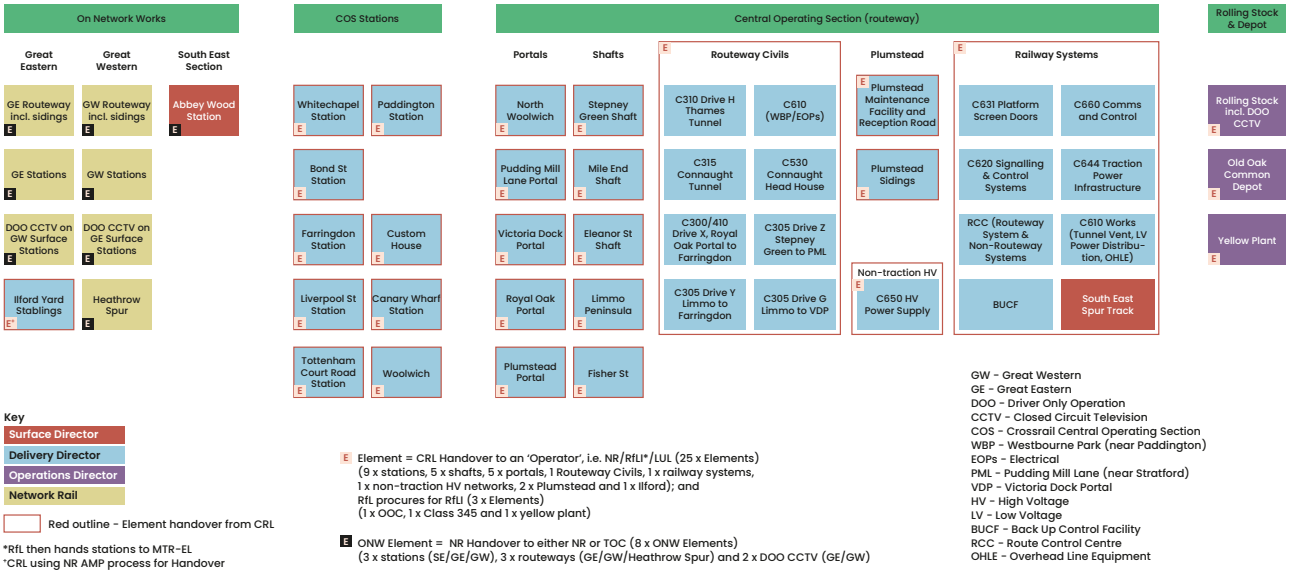

Figure 1 The complexity of size and volume

Crossrail retained direct control of the design for the tunnelling works and routeway civil engineering, while the new Tier 1 contractors developed their own detailed designs and started building. It's worth noting here that without this solid foundation of requirements and design in place, it is doubtful whether the Elizabeth line could have been successfully commissioned in 2022 with the original requirements intact. However, despite all this excellent up-front systems engineering, the programme found itself wrestling with complexity. The sheer volume of innovation taken on by the programme and the unprecedented levels of interconnectivity combined to create a burden of complexity that was fundamentally misunderstood at the heart of the programme.

There are three types of complexity and Crossrail found itself contending with all three. First there is the complexity of size and volume. Integrating over 30 construction elements, a new train, and a bespoke signalling and communication system, all running through 42km of new tunnels and joining to existing legacy railways, was challenging enough. Added to this was the complexity of interdependencies introduced by numerous delivery agents, working in parallel, drawing on the same resources, battling for access to rooms and delivery slots, and relying on upstream suppliers to complete before downstream activities could start. Major rail programmes to date have been used to dealing with these two types of complexity, so it is understandable how Crossrail maintained its composure and confidence as it approached 2018. The problem was that Crossrail had a third type of complexity to deal with, the complexity of system coupling that, combined with the other two, pushed the programme into uncharted territory.

In his book *Normal Accidents*: *Living with High-Risk Technologies* (1999), Charles Perrow explains various complex systems and categorises them based on how tightly coupled the functions of each system are and how complex the system interactions are. System coupling is a measure of how much tolerance there is in the system to cope with uncertainty while still delivering an output, and system complexity considers whether the system is linear and predictable (like an assembly line) or complex with the risk of unpredictable behaviour (such as an aircraft). Perrow originally classified railways as tightly coupled linear systems with segregated technology delivering each part of the process, combined with operators who had extensive knowledge of the whole system. As Figure 2 shows, even mass transit railways, while clearly more complex, are typically designed with a clear delineation between technical systems and can still be classed as linear. However, Crossrail demanded a much higher level of interconnection between sub-systems through the integration of software that automatically manages functions that were previously handled manually or semi-automatically. Crossrail is also a hybrid of mainline and mass transit railways, which to date have been clearly segregated with separate standards, safety principles and operational rules. Further complexity was therefore inevitable to produce a single system that works seamlessly across multiple railway environments while remaining compliant with standards that were sometimes found to be in conflict.

An example of all this is the platform screen doors and the way the train and signalling systems all combine to provide this function. Door opening is a safety-critical function for a railway but is straightforward to engineer. On Crossrail, however, this function was extremely difficult to achieve because the train has safety responsibility for door opening when outside the tunnel, but inside the tunnel responsibility is passed to the tunnel signalling system, which interacts with the train and then with the platform screen doors. Normal operation was engineered without difficulty but aligning all three complex sub-systems, engineered by three different companies (train, platform doors and signalling system) to manage this function in all possible scenarios (e.g. with a train door failure or a platform door failure) took considerably longer than expected. After over one year of software iteration and testing, further unforeseen problems were then found during systemwide testing outside of the tunnel. Furthermore, the arrangements for failed door isolation and the interaction of the platform staff with this function required further late changes to all the 432 platform screen doors, and an update to the platform control processes and additional training for platform operations staff.

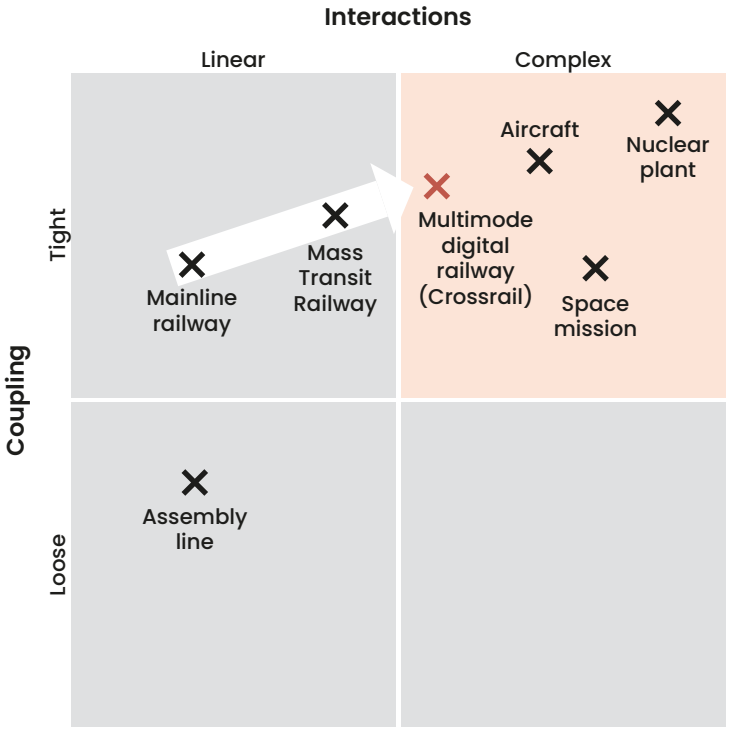

Figure 2 Increasing complexity of coupling of railway systems

This is just one example of the complexity arising from system coupling that Crossrail encountered; many more issues were discovered and resolved before the line opened. Future projects are likely to face similar complexity challenges to Crossrail as the prevalence of digital software systems increases and suppliers continue to move more and more functions of a system into software; even the train headlights on Crossrail are controlled by software. The important thing to consider at the outset is how the complexity of the system is measured and tracked during its design development, whether it can be reduced by removing functions from integrated software where possible, and asking at what point system complexity is likely to affect the delivery strategy, the schedule and, ultimately, the cost.

3 Contracts and delivery strategy

No one can deny that Crossrail is an incredible feat of civil engineering. During its initial construction, the programme did an amazing job integrating the construction of the tunnels through subterranean London and clearing the way for new stations in the heart of the city. The team also smoothly handled the integration of the programme with local authorities, utility companies, developers, regulators, other railways, business owners and government departments, to name just a few of the many stakeholders involved.

Figure 3 shows a timeline of Crossrail from 2006 through to 2022. When looking at the earlier years, you can see that the programme started strongly. Canary Wharf station was the first project to start, contracted to Canary Wharf Group shortly after Royal Assent was granted in 2008, and this was followed in 2009 with the framework designers for the tunnels and the tunnelling contracts in 2010.

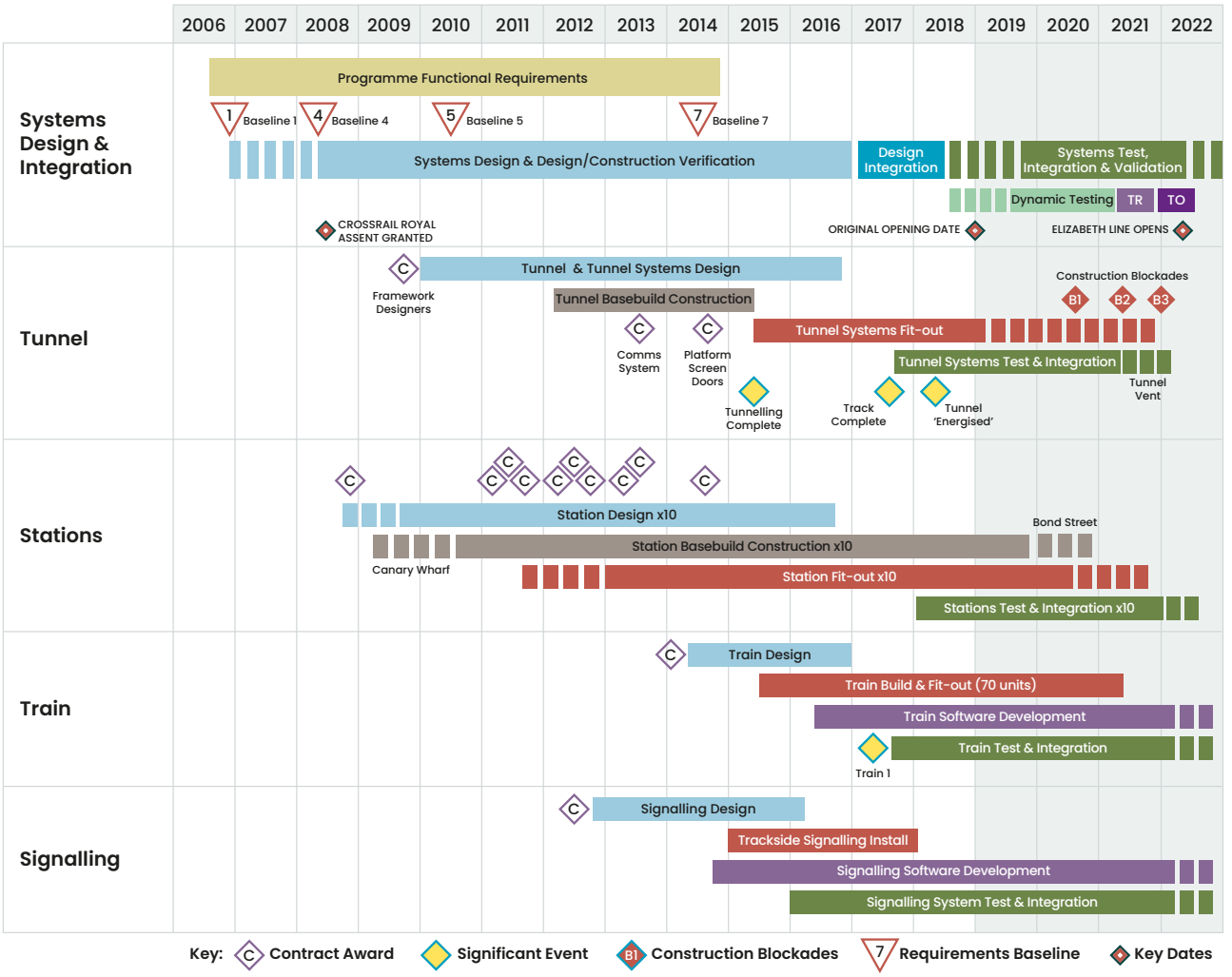

Figure 3 Crossrail timeline 2006–2022

Seven years after the programme started, the tunnels were completed on 26 May 2015, and this is when alarm bells should have started ringing. Three years to install, set to work, integrate, and assure an entirely new underground railway system of the size and complexity of Crossrail was highly optimistic. Individually, each supplier could demonstrate that three years was sufficient to complete their works, but once the challenges of concurrency were fully understood and common constraints such as unfettered site access, daily power isolations and the scarcity of commissioning resources became a reality, it is clear to see with hindsight that the plans for a December 2018 opening were fundamentally flawed. Looking at the timing of the contracts in Figure 3, you can see that the award of contracts was prioritised based on the logical sequence of civil engineering and construction. It appears that system complexity and integration was not considered as a significant risk driver for the programme at that time; if it had been, Crossrail would have started systems procurement much earlier. It is also interesting to note that the contract for the platform screen doors was the last major contract to be let, in 2014. Most of the station contracts were let before any of the complex systems, which meant that the design of the most complex parts started late, pushing most of the risky integration into a small window just before the planned opening date. As a result, the track wasn't completed until 2017 and the tunnels were not energised until early 2018, which gave insufficient time for Dynamic Testing, Trial Running (TR) or Trial Operations (TO).

The concurrency issue was further compounded by the train, which was delivered in 2017 but this created time constraints for integrating the safety critical train and signalling software systems. Safety-critical software systems are developed as global product lines, typically to an annual release strategy supporting a portfolio of projects for each supplier. A system as complex as Crossrail would require several iterations of integration testing and software rework before reaching an acceptable level of performance, and this ultimately influenced the critical path of the programme.

Another mistake Crossrail made in its original delivery strategy was to focus on delivering and commissioning the entire system at once. London had just delivered the Olympics, which might have influenced this strategy, but considering the complexity challenge, a new aircraft carrier or nuclear power station would not be commissioned overnight using a 'big-bang' approach. Complex systems go through several stages of testing, assurance and operator familiarisation to build confidence in the integration as the system comes together. A safety-critical railway is no different, and something as big and complex as Crossrail clearly needed a staged approach to commissioning, validation and assurance.

Finally, it's important to note that because the system contracts were let relatively late, you can see that from 2015 the system design and construction activities began to diverge. It wasn't until 2017 that designs were available in sufficient detail for the Chief Engineer to review, integrate and validate them against the system requirements. By then, construction was at an advanced stage, but over 1,000 design changes were identified to achieve the required system performance and to solve interface issues. Unfortunately, with schedule pressures mounting, there was a reluctance across the programme to incur delays to accommodate what was regarded by many as new scope, and this issue was compounded by over-reliance on the contracts to deliver integration. The understanding at the time was that the contractors would naturally align and would integrate and commission the system, and this was all specified in the contracts, with Crossrail supporting and co-ordinating the integration effort and applying a 10% check of assurance evidence. This arms-length, thin-client approach was effective for isolated conventional systems, but for the novel complex safety functions, distributed across multiple software systems, the suppliers simply did not have the visibility, understanding or commercial mechanisms to enable them to do this effectively.

By mid-2018, most of the construction works had been completed yet all the integrated systems remained incomplete, and many were still months if not years away from being ready to undergo their final integration testing. It became clear that the programme was in trouble and, after a brief hiatus and after securing additional funding, the programme restarted with a new CEO and senior team in place to lead it through to completion.

4 Grasping the nettle

In December 2018, it was announced that Crossrail would take on the role of 'Systems Integrator' and would re-establish an authoritative 'guiding mind' at the heart of the programme. The immediate priority was to establish a new Delivery Control Schedule (DCS) and to work out how much more time and money would be needed to open the railway. The Crossrail team also needed to be rebuilt and the supply chain briefed and re-engaged.

In terms of the systems integration challenges this brought, there were three main areas to focus on. First, a dedicated systems integration team needed to be established quickly to identify the minimum scope and functionality required to open the railway, and to then turn this into target configurations and a migration plan. The second challenge was to understand where the software development and software integration had got to, unblock critical boundary issues, and develop a software-release strategy through to the opening and beyond. The third challenge was to check the Testing and Commissioning (T&C) programme, understand how that fed the assurance work and ensure all the integration tests were planned to deliver the assurance evidence required for authorisation.

It's important to recognise that the Chief Engineer and his team at the time had a lot of the bases already covered, but due to the divergence between construction and design, a lot of the technical leadership on the programme had become marginalised and was now focused on recording non-conformances and enforcing compliance. Therefore, the approach when rebuilding the team was one of augmentation rather than wholesale restructuring, with most of the additions being made to deal with establishing clear configurations for each stage and becoming an intelligent client in software integration and systems testing.

The new systems integration team was hand-picked from the technical consultancies and from within Transport for London, with no single organisation having all the skills or proven levels of relevant experience required by Crossrail. Most of the new team members had extensive experience of integrating and assuring London Underground metro systems as well as broader experience with other complex software and hardware systems, such as aircraft and helicopters. Key people were also seconded from Transport for London to lead on critical integration challenges, such as testing and commissioning and cyber security. A Technical Programme Office was also established to create and maintain the technical reporting, metrics, outstanding scope and defect logs, which were crucial to the configuration management of the system through to completion.

4.1 Scoping, sizing and staging

Moving to a staged delivery approach was a huge change and affected every corner of the programme. The job of carving everything up into stages and checking everything aligned was initially daunting, and it took some time to convince the organisation that the complete railway system and its assurance evidence was not all going to turn up at the same time as had been expected. Instead, a progressive approach to testing and assurance would be required and then repeated for each configuration stage.

Initial work identified the earliest opening configuration, which demanded that the tunnel systems had to be 100% complete but trials could commence with stations at a minimum configuration, allowing for safe evacuation of a test train. Significant work was also carried out to define the minimum entry and exit criteria for each configuration stage, which was essential to align the whole programme on what had to be completed next and what could be left for a later date. This shift to focus everyone on the outputs of the railway for the next stage was fundamental to regaining control and rebuilding confidence across the programme. As Crossrail approached its first major milestone of 'Trial Running' in 2021, a

complete *System Description for Trial Running* was produced that underpinned the safety assurance and ultimately led to the endorsement of the *Risk Summary Statement* and the *Declaration of Control of Risk*. Both documents were essential requirements for the operator and duty holder of the line, who became accountable for the railway at that point.

Figure 4 shows the approach taken to deliver the works through Trial Running, Trial Operations and into Passenger Service. For each stage, the minimum requirements and risk profile of the railway increased. For example, for 'Trial Running', the railway was still undergoing 'proving', so there were no passengers. Without passengers, the platform train interface risks were minimal, meaning the platform screen doors did not need to be in their final end-state configuration. Similarly, with only a handful of drivers and testers moving through the railway, the tunnel systems did not have to be 100% complete for 'Trial Running' but it had to be proved that they were sufficiently safe, operable, maintainable and reliable for a 'Trial Running' railway. With each stage, the risk profile increased and, hence, the output requirements and burden of proof increased accordingly.

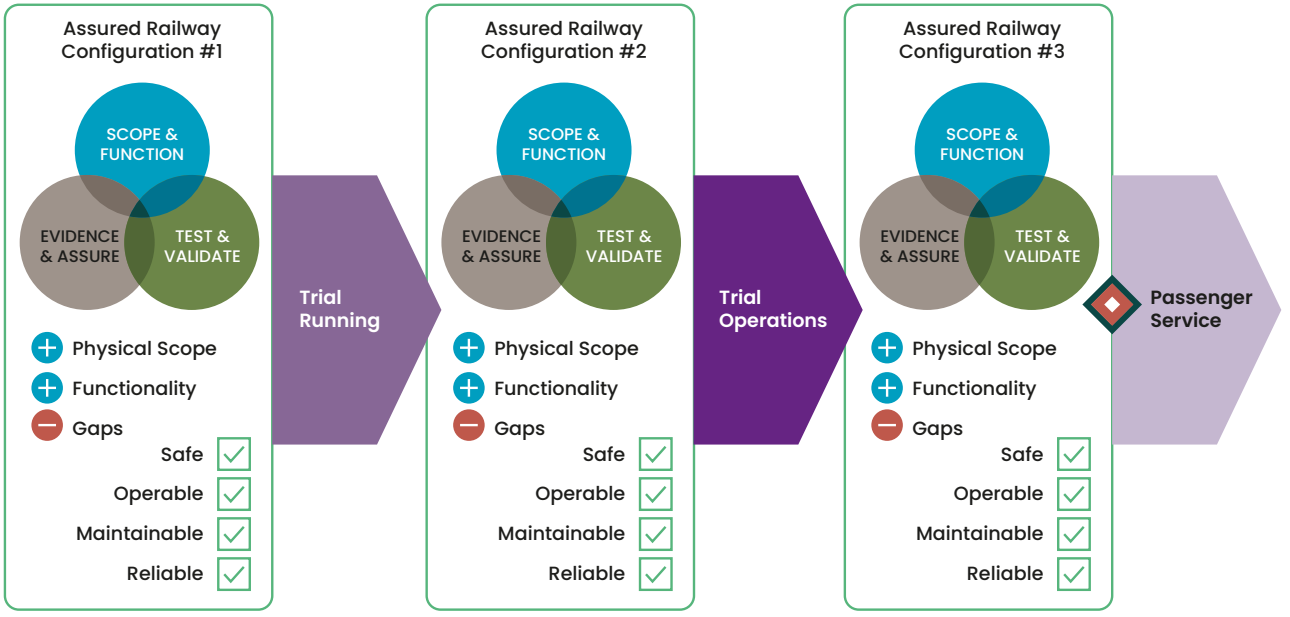

Figure 4 Crossrail layers and phases of integration

One of the key challenges Crossrail faced was reaching a consensus with the operator and maintainer on the minimum configuration for each stage, and translating this into clear requirements for physical scope, tested and proven functionality, and the assurance evidence required to support the interim safety case and Declaration of Control of Risk. In addition to tracking the scope, functionality and evidence, it was just as important to track the gaps in functionality, incomplete snags and missing assurance evidence, and to prove these were minimal and could be accommodated in the short term by the operator and maintainer. It was also important to quantify the remaining works-to-go at each stage and to prove that there was still sufficient system access available alongside the emerging priorities of maintenance, training and familiarisation required by the new operator.

4.2 Building an integration 'Plateau'

The successful opening of Crossrail relied on the integration of four complex software sub-systems: the train control system produced by Bombardier Transportation (now Alstom); the Bombardier ETCS signalling system, which was also the master signalling system; the CBTC metro signalling system from Siemens, which operated under the supervision of the ETCS system; and the Platform Screen Door system produced by Knorr-Bremse. Together, these safety-critical sub-systems are at the heart of the new 'digital railway' and handle many of the critical functions including train movement, the platform/train interface, transition between adjacent railways, passenger and customer information management, timetabling, track possession management and safety communication.

In 2018, the four sub-systems were being developed in relative isolation by the three companies and early testing had highlighted up to 40 problems with the integrated system, with over half of these considered to be 'mission critical'. The individual suppliers were working hard to fix their own bugs and to optimise their own sub-systems, but the activity was unco-ordinated and collectively they were struggling to optimise the whole system at a railway level; effectively, there was no 'guiding mind' for the integrated software system. Crossrail stepped up to take on the role of 'Systems Integrator' and to provide dedicated client-led engineering management of the integrated solution. It did this by establishing an integrated Plateau[1] team consisting of the senior engineers from each of the suppliers plus representatives from the driver and operator communities, led and supported by a Crossrail team of specialists. Figure 5 shows how the team was structured to provide a safe space for technical collaboration, problem-solving and optimisation, and operated independently and before the individual suppliers' contracts (note: the Platform Screen Doors team was integrated at a lower level within the Triage and Testing and Commissioning (T&C) functions).

1 'Plateau' is the term used in the Canadian aerospace industry when aircraft suppliers are brought together on a common level to solve complex systems integration issues. It was suggested by Danny Di Perna, who at the time was the President of Bombardier Transportation. He had spent his early career integrating aircraft systems and working in 'Plateau' teams.

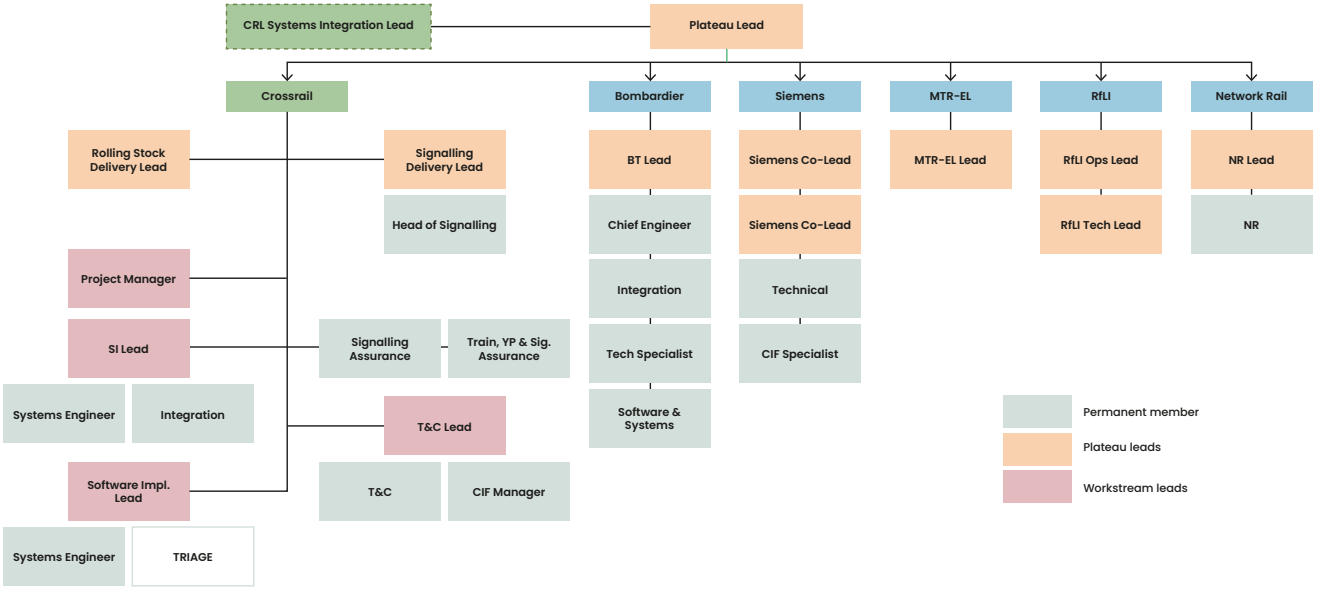

Figure 5 The integration Plateau team

After resolving most of the 'mission-critical' problems, the Plateau team focused on optimising the software release strategy to simplify the number of concurrent builds of software and to align the bug fixes into target configurations. It also provided a better collective understanding of the lead times involved for each type of bug fix, how these varied for each sub-system, and how each sub-system was assured and independently verified by an Independent Safety Assessor (ISA) every time a change was made.

As with home computer systems, safety-critical systems are engineered in layers. At the core there is the operating system, which is known as the 'product-level' software. The product level is engineered for a global market, typically on an annual development cycle that means any changes to it can take between 9 and 12 months to achieve. On top of this, suppliers design an 'application layer' that is unique to the specific railway. Application-layer changes can take between three and six months to implement and test, although changes to configuration data can be handled within a matter of weeks. There is additional work on top of this to provide independent system-level assurance that can take up to 17 weeks if it affects the safety case of the integrated train.

In April 2019, Crossrail was under pressure to declare an opening window and to confirm its new budget requirements. The Plateau team was still being formed and the full extent of system coupling and complexity had yet to fully come to light. Therefore, Crossrail relied on industry rules of thumb and benchmarking to forecast the critical path through integration to opening. Figure 6 illustrates the ongoing challenge faced by Crossrail to define an opening window while dealing with the uncertainty of the software development. The initial 2019 DCS shows what was understood to be true at the time by some of the best minds in the industry, and is a lesson in what happens if complexity levels are left unchecked and the supply chain is left to guide software integration. Drawing on five recent metro railway projects, a period of 15 months was initially identified to complete the systems integration. Based on the number

of bugs and the software development timescales, Crossrail assumed there would be a further five iterations of the software, which suggested that 19 months would be adequate to complete the integration, pointing to an opening date around the middle of 2021. It took a further six months of work in the Plateau team to fully understand the complexities and to translate this into realistic plans, resulting in an updated DCS in September 2020 that targeted an opening date in December 2021 with a probability of 50% (P50). While the original 2019 forecast was correct for the number of software iterations, some of the bugs required software changes at the product level, which were also discovered later in the programme after the COVID-19 shutdown and the restart of Dynamic Testing in the summer of 2020. Although the majority of the schedule contingency was used up, the teams developed innovative ways to achieve the 2020 plan, through a programme of system testing using a train, during the Trial Running phase, which was essential to flush out and resolve the final round of bugs in the system during 2021.

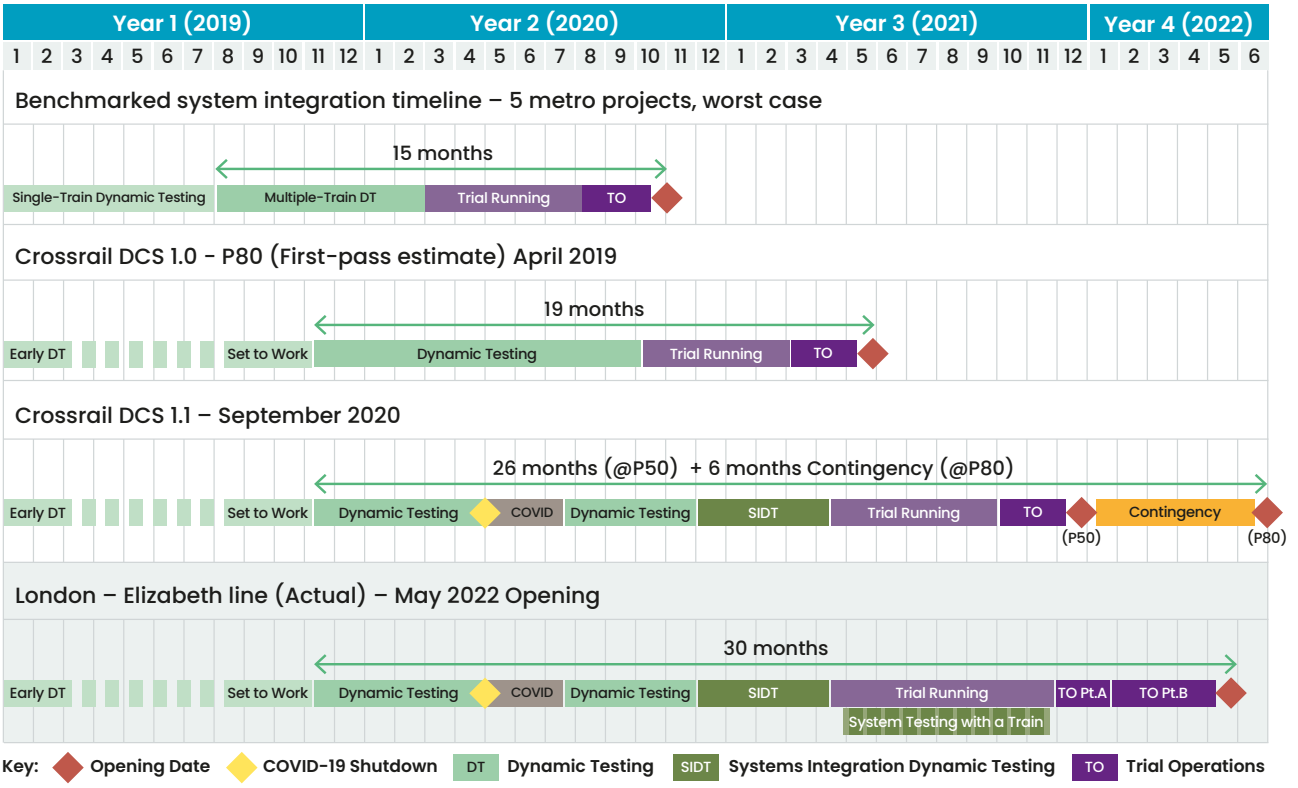

Figure 6 The impact of complexity on software iterations and timescales

Over time, the Plateau team evolved into a strategic planning function for future software deployment, and it now controls all planned software releases. Figure 7 shows the level of sophistication and control the client organisation now has over the software development and release strategy, which also includes maximising the use of the Crossrail Integration Facility (CIF).

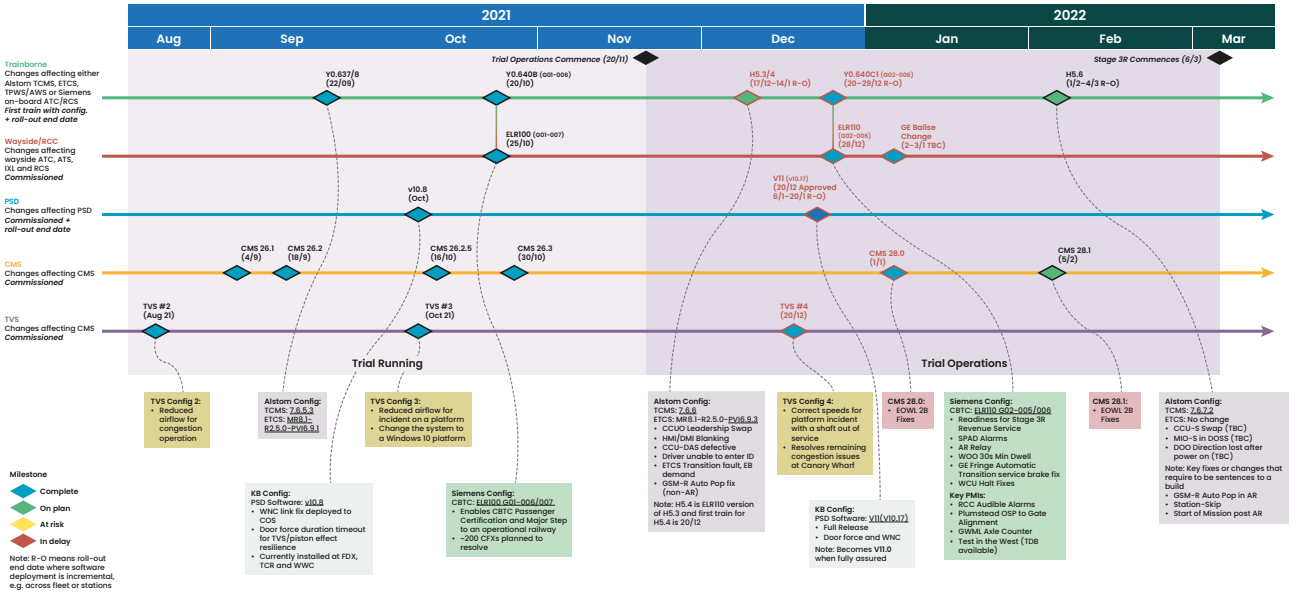

Figure 7 Crossrail integrated software release strategy

The CIF is an integrated test environment allowing many of the integration tests to be simulated and performed before rolling out the finished software onto the live railway. Specified and funded by Crossrail and hosted at the Siemens site in Chippenham, the CIF was an essential component of the integration testing. The CIF consists of product from Siemens, Bombardier (now Alstom) and Knorr-Bremse integrated with real-time simulations of the Rail Control Centre (RCC)[2], two train-driving cabs and the maintenance access system. It was used extensively by testing and commissioning teams, software developers and the future operators to flush out the issues, and to develop the reliability and performance levels required. The system is also capable of automatic operation and can run an intensive 30-trains-per-hour virtual train service continuously over many days to stress-test the software. Following the opening of the Elizabeth line, the Plateau and CIF facilities have transferred from Crossrail to the Elizabeth line team and continue to be used to manage in-service software updates on the live railway.

In 2020, a second Plateau team was established to co-ordinate the commissioning of the station Supervisory Control and Data Acquisition (SCADA)[3] systems back to the RCC. While not as technically complex as the train/signalling/platform screen doors, commissioning thousands of controls across eight stations in one year with scarce testing and commissioning resources was a wicked problem of 'complexity of size and volume' and 'complexity of interdependencies', and hence required a client-led approach to ensure success.

2 The RCC for the Elizabeth line is based at the Network Rail Romford Rail Operating Centre and controls the Central Operating Section of the line on a 24/7 basis.

3 This system provides the nervous system for the Elizabeth line, allowing remote control and monitoring of thousands of functions, ranging from electrical switches to fire systems and CCTV cameras.

The tunnel ventilation system was the only other part of the system that could have benefited from better client co-ordination and direction through a Plateau. While the software releases were relatively straightforward and were tracked through the software Plateau, the problems discovered during integration testing on door forces and tunnel cooling were unforeseen, were tightly coupled to other systems and were complex in nature. With limited time to establish a third Plateau team before opening, a traditional approach to problem resolution was taken but, in hindsight, earlier intervention and a collaborative Plateau approach would have been beneficial.

4.3 Holding the mirror up

As the programme collectively focused on achieving the next target configuration, it was essential that Crossrail had a mechanism to track progress and to highlight areas of concern. The entry/exit criteria used to define each configuration stage were used to develop a 'patchwork quilt' (Figure 8) to consistently visualise progress towards each stage and to identify which elements had already achieved handover to the operator and maintainer. The quilt pulled its data from the Crossrail Electronic Data Management System 'eB', which was mandated to and used by all contractors and was therefore indisputable.

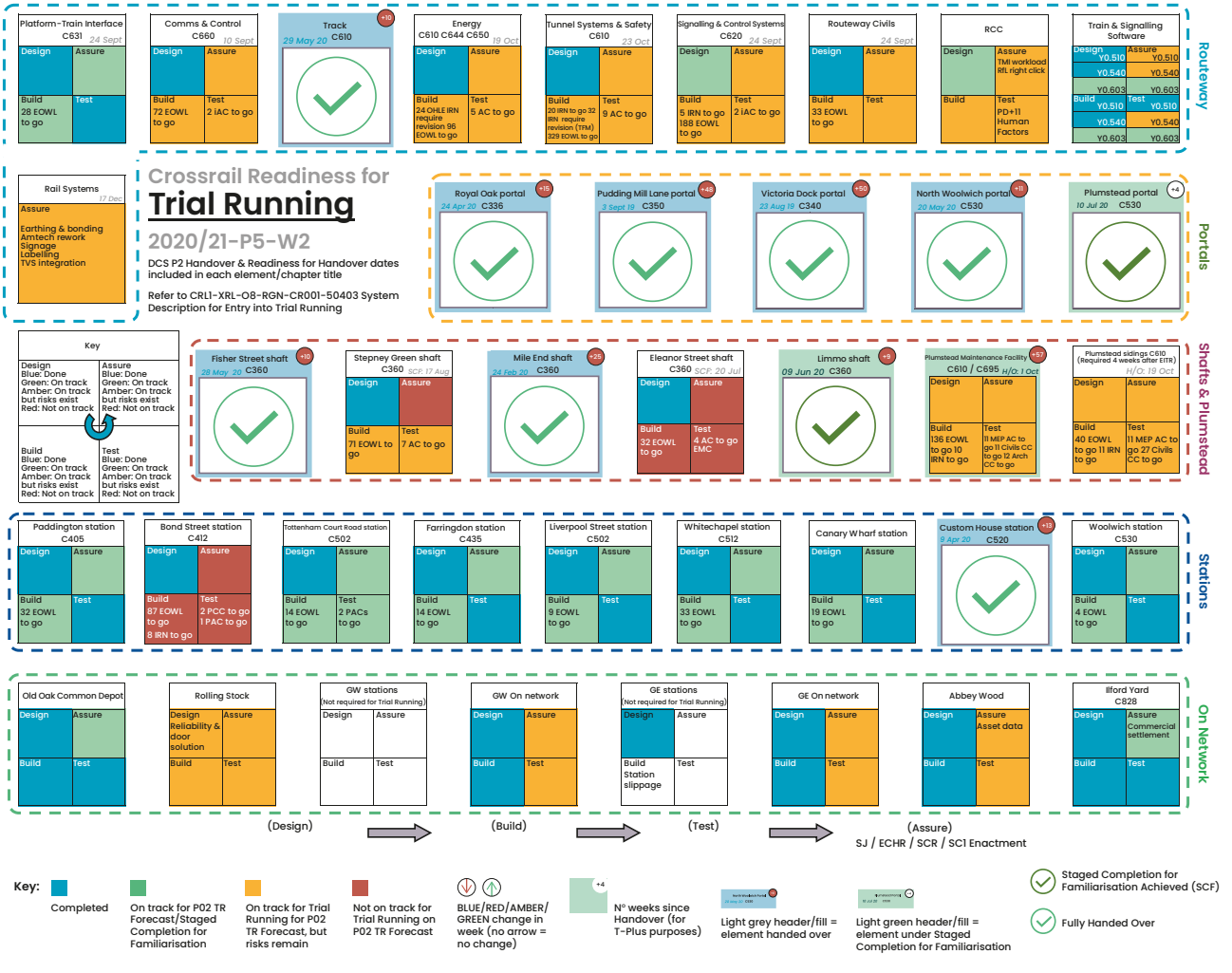

Figure 8 Programme summary 'patchwork quilt' for Trial Running

This approach allowed Crossrail to 'hold the mirror up' to itself and its supply chain to ensure that critical evidence, essential for the final assurance, was being generated and uploaded to eB. Each programme element was summarised by four squares of colour relating to the completion status of design, installation, testing and assurance. The report was also essential to re-establish the criticality and expected standards for assurance evidence and completion of works, which had unfortunately become confused or forgotten in the process of restarting the programme.

In taking a right-to-left view of the programme, Crossrail considered whether the test coverage provided by the contracts would be sufficient for assuring the integrated system. Contractors are generally not incentivised or in a position to undertake full test coverage and full integration testing, and after reviewing the contracted test coverage against the system-level requirements, a whole suite of additional and essential integration tests were identified. These tests were referred to as the routeway integration tests (RWIT) and were complex to define, plan and manage; therefore, as with the Plateau initiative, Crossrail stepped up to lead the RWIT phase, supported by the supply chain. Similarly to the way the Plateau team optimised the software deployment plan, the testing and commissioning team did the same, taking a series of competing priorities and finite testing resources, and optimising the railway testing and integration activities to achieve the next configuration stage. The team was strengthened to ensure it could provide testing logistical support and planning services to the programme as well as integration test leadership for the RWIT. It was also important that the team remained independent and, like the Plateau team, driven by the optimisation of the whole and not by individual supplier contracts.

One of the most important lessons learned during the integration testing phase was to maximise the use of off-site testing. Despite having the Crossrail Integration Facility, the system was not validated, meaning it could not be used to generate evidence that could then be used for assurance. Instead, all tests had to be proven and evidenced on the live Crossrail infrastructure. The CIF was used to carry out initial confidence testing and to investigate integration issues, but every test still needed to be conducted in the live environment. The experience of managing and co-ordinating all this activity confirms that the tunnels are a pinch point for systems integration, and every effort should be made at the start of the programme to maximise the amount of testing and integration that can be done off-site, and to ensure the test results can be used for assurance.

Finally, it is important to consider when the infrastructure is ready to start testing. Due to schedule pressures, Crossrail started Dynamic Testing in 2018 before construction in the tunnels had been substantially completed. It is understandable why this decision was made, but in hindsight it was incredibly inefficient and required the testing and construction teams to continuously switch between a construction environment and a test environment. Crossrail adopted a 4-3 model (four days construction, three days testing) that was repeated throughout 2018 and into 2019. While the strategy provided early confidence in some of the integrated functions, with the tunnel systems only partially commissioned, many of the test scripts for the train and signalling simply could not be exercised. This meant that the train and signalling suppliers struggled to fill the allotted time with meaningful tests, which also delayed the discovery of hidden issues with the integrated software. Similarly to how Crossrail and the operators and maintainers defined the entry/exit criteria for Trial Running, it would have been advantageous to define the entry/exit criteria for Dynamic Testing and to clarify to the supply chain the minimum requirements for the construction fit-out of the tunnels before commencing the integration of the train and on-board signalling systems.

5 Conclusions

For complex infrastructure projects involving ambitious levels of digital innovation there are seven key lessons.

5.1 You cannot outsource integration

Probably the biggest lesson from the experience of integrating Crossrail is that you cannot outsource systems integration and simply rely on others to handle the complexity and to optimise the outcome. Reliance on contracts with suppliers to handle the integration, even if they are world-leading in their field, will not give you an integrated system. Regardless of how well you manage the procurement phase, it is inevitable that silos will form over time, and the client will need to step up and provide a 'guiding mind' to ensure outcomes are optimised and integration issues are resolved. On Crossrail there was an over-reliance on the supply chain to co-ordinate and resolve issues between suppliers. This, combined with a tight schedule and a looming deadline, caused the programme to become siloed and insular rather than focused on delivering the whole.

Crossrail had built a very capable client team, but it just wasn't 'thick' enough in some areas to guide the whole solution; it lacked capability in some of the critical areas of integration, such as software engineering and integration testing. This was exacerbated by the design integration running in parallel with construction, which had started at risk, only adding to the challenge of keeping everything aligned. Not all infrastructure projects will need to build client teams as big as Crossrail; the choice of whether to become a 'thin' or a 'thick' client or to appoint an 'integration partner' will depend on the complexity of the technical solution, and the magnitude of the people and process changes being delivered. The critical thing here is to ensure that there is always enough experience and capability available in the client team to remain an 'informed client', and to provide a 'guiding mind' across all aspects of the programme.

5.2 Keep a lid on complexity

Left unbridled, complexity will end up driving everything on a major programme: the risk profile, the schedule and, ultimately, the budget. Projects naturally increase in their complexity as they get bigger and involve more concurrent activities and delivery agents, but complexity is also lurking in the less tangible parts of the system, such as the control software, the interfaces between systems and the assurance evidence. It is important to decouple complex parts of the system wherever possible, although for new digitally enabled infrastructure, this is likely to be difficult to achieve. One option that Crossrail considered but never implemented was investing in a conventional overlay signalling system that could be used to get the railway open and, once the digital system was fully completed, could then be used as a backup system during incidents. This might sound like an ideal solution, but the reality is it would have just shifted the complexity of integration into the operational railway environment, significantly increasing the deployment risk and probably, in time, forcing the sponsors to accept a sub-optimal outcome.

If complexity cannot be avoided, it is important that the systems involved are procured as early as possible, and integration starts at the earliest opportunity and continues throughout the entire programme. It is also vital that the volume of complexity and change will not be beyond the capabilities of the client organisation, and the future operators and maintainers of the system.

Perhaps the best approach is to be an early adopter of new technology rather than an innovator. Many of the systems deployed on Crossrail were at the leading edge of new technology but had yet to be applied on a live project. This introduced considerable risk to the programme, as Crossrail was effectively acting as a catalyst for global research and development in rail technology integration. With that said, Crossrail will be regarded as a reference site for new rail systems technology for many years to come and this is likely to benefit the UK rail industry significantly over the next decade.

5.3 Integrate from the top

The silos that naturally develop as a major project evolves can eventually become a significant barrier to integration. Organisational boundaries are reinforced with contracts and at some point in the life cycle of a major programme, critical integration issues can become log-jammed. Integration is a dynamic, often painful, and emotive process; on Crossrail it required compromise and often rework to align parties, and it upset individual schedules and highlighted hidden costs. Fundamentally, systems integration is inexorably linked to the programme management of a complex major project. However, the two are often treated separately with systems integration seen as a technical activity added on to the hefty challenges of construction, schedule and cost control of a major programme.

Therefore, it is vital from the outset that integration is championed and sponsored by the CEO, the executive team and the programme sponsor, and that they recognise that integrating complex systems is often emergent and imprecise. It is also vitally important that the project and programme leadership understands systems integration sufficiently well to augment the programme delivery and systems engineering functions into a single delivery team. Systems engineering and systems integration always maintains the link back to the sponsor's requirements on behalf of the programme; it is not something that bookends the construction phase at the beginning and the end, it is continuous. It is also important to ensure that the ultimate signatories, such as the Chief Engineer, have a sufficient escalation route and are encouraged to highlight emerging integration concerns throughout the life cycle. Robust commercial and change management mechanisms must also be in place to optimise the outcomes of the programme across multiple contracts and to swiftly deal with conflict when it arises.

5.4 Take it one step at a time

Complex systems cannot be delivered using a 'big-bang' approach and will instead require a series of carefully considered stages to progressively build confidence in the system. From the outset, the delivery strategy must be aligned with the integration strategy, which in turn, needs to reflect the system complexity. If a system is comparable in complexity to other complex systems, it will undoubtedly require a similar number of stages of integration, rework, retesting and final acceptance. Each stage will need to be fully defined with the minimum target scope, functionality, testing requirements and assurance evidence requirements, and these must form the demonstrable criteria for staged acceptance and the achievement of contractual milestones.

While it is unavoidable that construction starts before the complete system is fully designed and validated, it is vital that projects take a staged approach and put as much emphasis on the step-by-step achievement of the testing and assurance evidence as they do on achieving physical construction milestones. There is often an urgency to demonstrate tangible progress, which can lead to a narrowing of focus and a gradual increase in technical

debt and outstanding assurance evidence. Left unchecked, this can lead to significant rework and lengthy delays during the final integration and assurance of the system. The provision of bespoke fire doors in the stations is a perfect illustration of this point. Proving the fire integrity of each underground station was critical to complete the assurance of each station prior to opening. Several years after their installation, it was discovered that many of the bespoke stainless steel fireproof doors installed to provide fire compartmentation had inadequacies in fire certification; the physical works had been prioritised over the assurance requirements. The only solution was to remove one of the huge doors from Liverpool Street station and send it to Germany to be burnt in a furnace to prove its fire integrity and to certify it for use. A replacement door was then manufactured to replace it. While this issue did not cause all of the delays experienced on Crossrail, it was one of many that compounded and added several months to the schedule and millions of pounds to the final cost.

For complex systems, you cannot afford to only focus on the physical completion of the asset and assume that certification and assurance can be sorted out at a later date. It's always better to deliver in stages and to ensure the assurance evidence is in place each step of the way.

5.5 Take a hard line on software

Procuring complex technology for a new railway will always be a difficult compromise between procurement rules, legacy technology and functionality fit. This means that most complex railway projects end up with a mix of technology from different suppliers and product lineages, which almost always creates bespoke development and unique integration challenges. Add to this the complexity of the global software development supply chains each system relies on, and the different procurement routes for rolling stock and fixed infrastructure, and client teams would be well advised to take a hard line when managing software integration.

It is vital that client teams develop the capability to be able to co-ordinate and optimise the delivery of each software release into a single integrated software deployment plan, covering all sub-systems and software suppliers. This also includes understanding the testing regime sufficiently well to ensure the amount of off-site integration testing and system assurance is maximised, and that test coverage is sufficient to prove the safety and performance of the fully integrated system. Left unchecked, suppliers will optimise the outcomes as they see fit for their sub-system without necessarily considering the whole. Suppliers also tend to be overly optimistic in terms of how many bugs they expect to find, and the severity and the number of rework cycles they expect to encounter, as the system undergoes on-site and off-site integration testing. These planning assumptions are always critical to the staging strategy. Ultimately, the projected final end date of the project will rely on the client's understanding of the 'find-to-fix' lead times for each software component and the number of software development cycles required to achieve a fully integrated system.

While the physical construction and installation of hardware typically drives the front end of the project schedule, the development, testing and integration of complex safety-critical software systems will inevitably drive the back end of the schedule, and hence the critical path to opening.

5.6 Build from left to right, integrate from right to left

The focus on logical left-to-right planning is essential during construction and ensures that earned value and productivity can be tracked as the works progress. But for a programme as long and complex as Crossrail, over time, this left-to-right approach to delivery can become ingrained into the culture of the programme, which can cause issues when you start to integrate.

Integration requires the opposite approach to construction, which can be at odds with what has become the norm over many years for getting things done. Integration requires a right-to-left approach to planning and delivery as the original requirements are reviewed, and the suite of tests is identified that will prove the requirements have been met. The priorities for construction are then driven not necessarily by the logical P6 plan but by the most efficient order of testing and validation for the next configuration stage.

In early 2019, before Crossrail had fully gripped the systems integration challenge, the programme was struggling to achieve construction productivity levels higher than 40%. Many of the worksites were juggling conflicting demands from numerous contractors for site access, power isolations and scarce resources, which resulted in most of the works being partially completed or cancelled on a daily basis. As the works became more concentrated and influenced the system more widely, the left-to-right approach was no longer capable of delivering predictable results. Towards the end of 2019, once the stages towards completion had been defined in sufficient detail and the constraints were fully understood, a right-to-left approach could then be taken to more efficiently co-ordinate the combined efforts of all contractors to deliver the minimum requirements for the next target configuration.

When a project is nearing the end of its construction phase and productivity levels begin to dip, it is important to recognise this dynamic and to adopt more right-to-left thinking and planning, to direct the priorities for construction and completion and to optimise resources to avoid the concurrency trap. On Crossrail, the terms ‘backward pass’ and ‘forward pass’ were used to confirm that the next milestones could be achieved through a logical P6 ‘forward pass’ of the plan and that, when delivered, the specific outcomes required for systems integration had been confirmed through a ‘backward pass’ from the assurance evidence and testing outcomes back through to the construction plan. While this approach inevitably created some tension within the project, the impact on productivity and schedule adherence was significant, and underpinned the on-time delivery through to the opening.

5.7 Grasp the nettle with both hands

Integration requires a hands-on client approach and a willingness and enthusiasm to understand the most complex parts of the system. On one hand, you will have the complex, tightly coupled parts of the system under your direct control and be prepared to lead cross-project integration teams such as the Plateau team. This must provide a focus for collaborative problem-solving, and for optimisation and prioritisation of the outputs according to your needs and not those of the suppliers. For complex integrated systems, you will also need to establish your own integrated simulation and test facilities as early as you can to increase the engagement and understanding of future operators and maintainers, and to consider how you will use them to integrate, simulate and prove the system has met the requirements.

On the other hand, you will need to hold a mirror up to the works, which reflects the assurance evidence that you expect to be in place to achieve authorisation and opening then, working backwards, right to left, the things you need to see delivered that will lead to the evidence being produced. Integration tests from suppliers are unlikely to be comprehensive so you will need to be prepared to step in and manage these directly. When writing the contracts for suppliers, it is important to consider how you want suppliers to behave at the end of the programme when there is a debt of technical assurance and evidence. The contracts used by Crossrail incentivised the completion of physical works but did not incentivise the collaborative participation in integration testing, the reduction of assurance debt or the production of final assurance evidence. Tiger teams had to be established to seek out and demand outstanding assurance evidence from suppliers, which fed the final assurance safety case, but it would have been far easier and certainly less expensive to incentivise the supply chain to deliver good evidence on time and to keep the technical assurance debt to a minimum.

Complex major programmes are now increasingly likely to face integration challenges like those of Crossrail, yet client teams may continue to be tempted to transfer the risks of integration back to the supply chain or rely on purely left-to-right planning. Systems are now becoming so interrelated and complex, individual suppliers no longer have the end-to-end visibility of how complex functions are delivered and how the whole system can be optimised. Therefore, for complex systems, 'grasping the nettle' is now an essential act of client leadership and should be integral to programme delivery, providing the focal point for programme optimisation and the staged delivery of outcomes.

Governance arrangements to complete the Crossrail project

1 Introduction

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The opening of the Elizabeth line on 24 May 2022 was a significant achievement for everyone involved in the delivery of Crossrail, including the Joint Sponsor team who oversaw the governance arrangements that supported the project through development, construction, commissioning and the successful transition into operations.

The Joint Sponsor team was established with staff from both sponsor organisations, the Department for Transport (DfT) and Transport for London (TfL), and was responsible for interfacing with the Crossrail project on behalf of the sponsors.

In this paper, as current members of the sponsor teams in DfT and TfL, we reflect on the changes made to the governance arrangements as the project progressed through recovery, completing the railway and project close, and describe the impacts of these changes.

We have identified lessons that we feel are beneficial for other major government-funded infrastructure projects, including High Speed 2, East West Rail, the Lower Thames Crossing and future investments including the Bakerloo line extension and Crossrail 2.

The paper includes the following sections.

- Section 2 provides an overview of the project, sponsorship and governance arrangements. The project governance of Crossrail Ltd, the delivery body, is not included in detail.
- Section 3 describes the recommendations for change that were made in 2018–2019.
- Section 4 explains the key governance changes in 2018–2019 and the impacts of these changes.
- Section 5 identifies further governance changes in 2020, driven by the operational pull to complete the railway.
- Section 6 describes the remaining priorities following the successful launch of the railway in May 2022 as we look to close the project.
- Section 7 identifies lessons learned from these changes that may be applicable to current and future infrastructure projects and programmes. A list of other relevant learning legacy papers and published good practice is also included.

In addition to the Joint Sponsors' perspective included in this paper, DfT and the Infrastructure and Projects Authority (IPA) have commissioned an independent lessons-learned review on the sponsorship of Crossrail. This follows from the 2019 report, *Lessons from transport for the sponsorship of major projects* (link: https://www.gov.uk/government/publications/lessons-from-transport-for-the-sponsorship-of-major-projects) Publication is expected later this year.

2 Project overview and sponsorship

The Elizabeth line

The Elizabeth line is the most significant addition to London's transport network in a generation. The new railway has transformed life and travel in London and the south east: it has reduced journey times, created additional capacity and transformed accessibility.

On 24 May 2022, the Elizabeth line opened with services between Paddington and Abbey Wood, along with existing services linking Reading and Heathrow with Paddington, and Shenfield with Liverpool Street, being rebranded as the Elizabeth line. On 6 November 2022, direct Elizabeth line services into central London from Reading, Heathrow and Shenfield were introduced, and the full end-to-end timetable is set to be introduced in May 2023.

The Elizabeth line runs for more than 100km – from Shenfield and Abbey Wood in the east through central London to Reading and Heathrow in the west. With a total of 41 stations, including 10 major new stations, the Elizabeth line connects London's main employment centres, and supports new journeys through central London out to Essex, Buckinghamshire and Berkshire.

The Elizabeth line is part of the TfL and national rail network, has interchanges with the London Underground, Docklands Light Railway, London Overground and National Rail services, and has increased central London's rail capacity by 10%.

The Elizabeth line is crucial to London's recovery from the pandemic, helping avoid a car-led recovery by providing new journey options, supporting regeneration across the capital, and adding an estimated £42bn to the UK economy. London is paying for most of the Elizabeth line, with nearly 70% of the total funding paid by London – made up of 30% from London's farepayers and around 40% from London's businesses – combined with 30% from government.

The Crossrail project

Crossrail Ltd is a subsidiary of TfL and is responsible for delivering the Elizabeth line railway, including the new tunnels, stations and rail systems. Crossrail Ltd was established in 2001 with its own Board to hold the Executive to account. Construction of the new railway began in 2009.

The Crossrail project is hugely complex, and it has been immensely challenging to deliver a railway of this scale that is safe and reliable for passengers, as well as fully integrated with the existing transport network at both the strategic and local levels. Crossrail Ltd has worked closely with industry partners, including Network Rail, responsible for delivering the sections of route to the west and east that were part of the existing rail network, and Heathrow Airport Limited, as well as other key stakeholders. The new railway is regulated by the Office of Rail and Road.

Crossrail sponsorship

The sponsors of the Crossrail project are TfL and DfT, the organisations accountable for making the case for investment, securing funding, specifying the project's requirements, and ensuring that the project benefits and outcomes are realised. They are also accountable for ensuring that the project is governed effectively.

The interests of the sponsors were brought together through a comprehensive and detailed sponsors Agreement, which was negotiated and agreed in 2008. This sets out the overall management, ownership and governance of the project, including the roles and responsibilities of each sponsor, the risks to be managed by each and how things are managed over time. The role of DfT as sponsor alongside TfL meant that central government would have oversight of delivery, as well as sufficient influence on the project objectives and outcomes, to ensure that DfT outcomes were balanced with those of London.

For the delivery phase of Crossrail, the sponsors established a governing body in the form of a Sponsor Board.

The Sponsor Board was established by the sponsors as a forum to co-operate to procure the development and implementation of the Crossrail project with specific responsibility for making decisions in consultation with the respective sponsor organisations as needed on matters relating to the Crossrail project, including:

- approving any changes to the Sponsors Requirements
- approving any amendments to the Project Development Agreement
- approving the appointment of independent Non-Executive Directors and the executive Chair, Non-Executive Chair and Chief Executive Officer of Crossrail Ltd
- approving the final versions (prior to their execution) of principal project documents
- issuing review notices following each project review

The Sponsor Board was also a strategic forum for sponsors to engage with the Crossrail Ltd Executive, the Project Representative, and others as appropriate to stay informed on project progress and risks, and support the delivery where possible.

Sponsors Requirements were agreed and included in the Project Development Agreement agreed with Crossrail Ltd in 2008. Crossrail Ltd adapted these into functional requirements used to specify the outputs for the railway.

The purpose of the Sponsors Requirements was to:

- establish and describe the sponsors' high-level requirements and objectives for the Crossrail project
- provide a basis for Crossrail Ltd and the sponsors to consider and resolve how developing, competing or subjective requirements were to be interpreted
- set out the minimum requirements that the Crossrail services must achieve
- provide the baseline for the sponsor-level change control mechanism
- provide the basis for monitoring Crossrail Ltd's role as programme manager and integrator as defined in the Project Development Agreement

The sponsors commissioned a Project Representative (P Rep) to provide independent advice on project progress, risks, changes in scope, reporting outputs and resource capability.

The P Rep was responsible for ensuring that the sponsors were adequately informed of the progress of the implementation of the Crossrail project, including:

- advising on risks of a funding shortfall
- providing independent, informed advice on progress against time, cost and quality
- providing oversight and analysis on changes in scope
- monitoring Crossrail Ltd's compliance with its environmental and sustainability commitments
- reviewing Crossrail Ltd's reports and undertaking audits and reviews
- advising on the capability and resources deployed by Crossrail Ltd

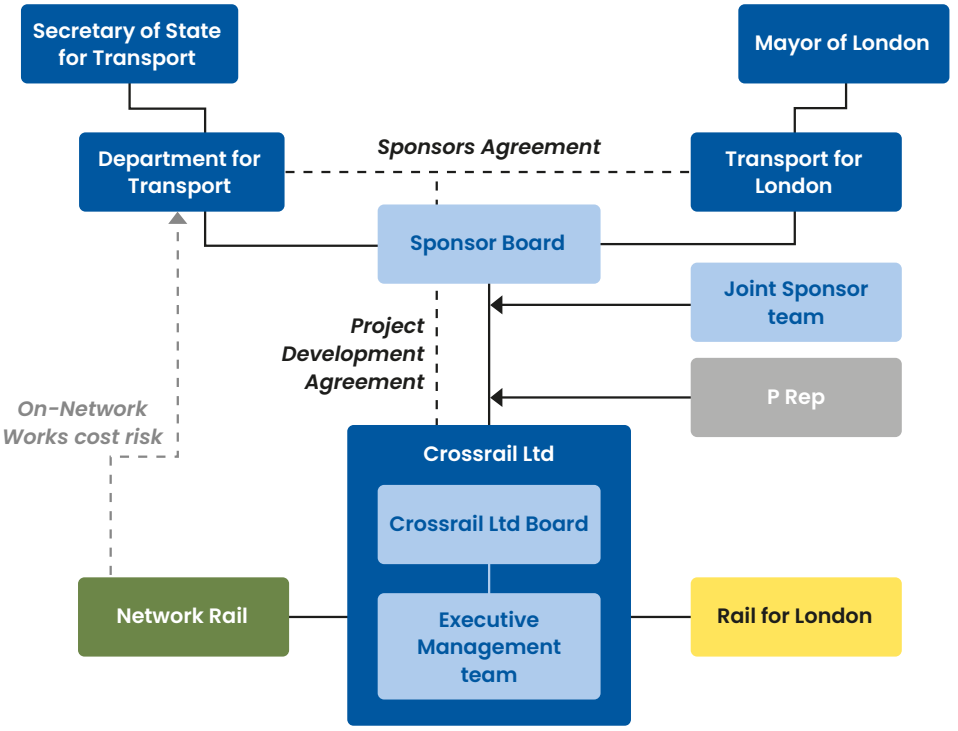


Figure 1 Crossrail governance arrangements pre-October 2020

Governance arrangements during construction

In 2014, the National Audit Office's (NAO) review of Crossrail governance found that the governance structures were in good stead and set a strong foundation for delivery. It concluded that DfT worked together with TfL and Crossrail Ltd to create effective oversight and the project was making good progress.[1] An overview of the governance arrangements is outlined in the NAO report.

An overview of the governance arrangements is also included in the 2016 Learning Legacy paper, *Lessons learned from structuring and governance arrangements: Perspectives at the construction stage of Crossrail.*[2] The 2016 paper found that the independence and autonomy delegated to Crossrail Ltd by sponsors, separating it from the delivery body, had provided an effective solution to support the realisation of project outcomes. This was enabled by governance arrangements and project agreements that appropriately allocated responsibilities and management of risk.

The paper's assessment reflects the suitability of the governance arrangements as the tunnelling and other construction activities were coming to an end. Looking forward to the responsibilities and risks that were emerging as the project evolved to focus on systems integration and railway commissioning may have led to a different conclusion. In hindsight, a warning sign that the governance arrangements may not have remained suitable was that although sponsors raised concerns and commissioned independent reviews to investigate the cost and schedule, the Crossrail Ltd Board continued to provide assurance to sponsors that everything was in place for a timely and stable opening in December 2018, despite the reporting of increased costs and risks and Crossrail Ltd replanning activities while maintaining key schedule milestones.

1 https://www.nao.org.uk/wp-content/uploads/2014/01/Crossrail.pdf
2 https://learninglegacy.crossrail.co.uk/documents/lessons-learned-from-structuring-and-governance-arrangements-perspectives-at-the-construction-stage-of-crossrail/

3 Recommendations for change

After prolonged reassurances that the project was on time, Crossrail Ltd announced in August 2018 that a revised schedule was needed to complete the final infrastructure and the extensive testing required to ensure the Elizabeth line opened as a safe and reliable railway. This announcement was disappointing and raised the question about the suitability of the governance arrangements that gave Crossrail Ltd high levels of autonomy.

Sponsors agreed that there was no other realistic prospect than to get the project finished. Pausing the project was not considered a realistic option, as the project costs would increase and benefits for passengers would be delayed. Sponsors accepted that the governance arrangements in place had not captured the most pertinent risks to the project as it progressed. Crossrail Ltd had failed to fully understand the complexity of the work to integrate the elements of the new railway. Therefore it was agreed that changes were needed to the governance to improve project delivery and oversight.

In September 2018, sponsors commissioned an independent review into Crossrail Ltd's governance and financial and commercial arrangements.

- KPMG (2019) *Independent review of Crossrail – Finance and Commercial* and *Independent review of Crossrail – Governance* (link: https://tfl.gov.uk/corporate/publications-and-reports/crossrail-project-updates)

The review identified that the governance arrangements did not sufficiently address the evolving needs of the project from the changing balance between construction, systems, integration and operational readiness activities. The review made recommendations for changes to align the governance arrangements to the expected project needs through to completion and to facilitate more effective oversights from the sponsors. Given the life cycle stage and complexity of the remaining work, a completely new governance structure was not considered appropriate as it would potentially introduce significant risk to the project.

The themes below summarise the recommendations identified from the independent review of Crossrail. The Sponsors considered these themes when identifying and implementing changes in response to the project challenges.

Themes	Description
 Accountability	Roles, responsibilities and accountabilities between the sponsor organisations and the delivery body need to be clearly defined at all levels to avoid confusion and define the level of autonomy granted to deliver the project.
 Behaviours and relationships	Poor behaviours and decisions are harder to pick up than problems with plans or processes. It is important that strong relationships and trust are built up both within and across stakeholders, without having a culture of blame when issues emerge.
 Openness and transparency	Governance structures should promote transparency and openness to ensure the risks and issues are reported in a timely and sufficiently clear manner.
 Skills and capability	Governance arrangements need the appropriate expertise and skills in the right place for successful project completion.
 Project controls	Project controls and assurance must be appropriate for the stage of the project. Project reporting must be timely, realistic and insightful.

4 Governance changes and impacts

The changes implemented in response to the review recommendations are summarised in the table below along with the effects of these changes on the continued delivery of the project.

While a new governance structure was not implemented at this time, the aim of the changes was to align Crossrail governance with the status of the project and enable more effective sponsorship oversight.

The main changes included:

- **Changes to the composition of the Crossrail Ltd Board** to increase its effectiveness and set out priorities and expectations with the Chair and Deputy Chair for the remainder of the project.
- **Strengthening the Executive team** by appointing a new Chief Executive and Chief Financial Officer. Further project changes included appointing an experienced Programme Director, Technical Director and Project Controls Director.
- **Strengthening the P Rep** by bringing in new skills and capabilities, setting out expectations and agreeing a revised approach for more proactive and inclusive challenge of Crossrail Ltd and reporting to sponsors.

At this time, the sponsors focused on increasing levels of oversight and transparency on the project. The changes resulted in greater scrutiny and challenge around decision making and an increase in the level of assurance provided. The governance changes also strengthened the oversight of the project, bringing the sponsors and Crossrail Ltd (including the Crossrail Ltd Board) closer together, while allowing Crossrail Ltd to maintain autonomy to focus on delivery and integration of the railway systems.

Themes	Changes implemented in 2018 and 2019	Impacts of changes
 **Accountability**	• Appointed a new Crossrail Ltd Board Chair with the remit to "ensure Crossrail Ltd takes accountability and responsibility for the delivery and integration of all aspects of the project required for an end-to-end railway". • Appointed a new Chief Executive Officer with extensive knowledge and experience of delivering major signalling and systems integration projects to lead the hugely complex project through its final phases, including Trial Running, Trial Operations and the opening of the Central Section. • Re-established the priorities and expectations of the Crossrail Ltd Board and Sponsor Board.	• The appointment of new people into leadership roles and the reassertion of accountabilities enabled the project to move forward despite challenges. • Existing arrangements were strengthened rather than changed, which provided stability to the project.
 **Behaviours and relationships**	• Set cadence and relationship between governance meetings (Crossrail Ltd Board and Sponsor Board arranged with the target of no more than five working days between meetings). • Established sponsor debriefs at Crossrail Ltd Board and 'open door' approach to management meetings including visualisation meetings. • Enabled direct engagement between P Rep and Crossrail Ltd's leadership.	• Trust and confidence between the sponsors and Crossrail Ltd were rebuilt. • Risks and issues were dealt with more effectively due to informed and timely decision making. • Expectations set with leadership were cascaded through the delivery organisation. • The rebuilding of Crossrail Ltd relied on the secondment of TfL staff and meant that TfL ways of working were adopted to complete the project. • The closer working relationship between sponsors and Crossrail Ltd enabled sponsors to support and influence engagement with the supply chain.
 **Openness and transparency**	• Crossrail Ltd introduced a visual management process (to track progress with delivery) and 'war room' (to provide strategic oversight). • Crossrail Ltd began to share the weekly dashboard with sponsors and key stakeholders and meet regularly with the TfL Commissioner, the Deputy Mayor for Transport (every two weeks) and the Mayor of London (every six weeks). • Crossrail Ltd Board and Sponsor Board minutes were published. • P Rep reports and scrutiny reports were published. • Regular engagement with London Assembly Transport Committee and Public Accounts Committee was established. • Stakeholders representing key organisational interfaces were invited to attend Sponsor Board when required.	• Sponsors had enhanced project oversight while maintaining separation between them and Crossrail Ltd. • Providing sponsors with visibility of the management information ensured consistency and timeliness of messages while minimising the reporting burden on Crossrail Ltd, as bespoke reports were not required. • Information was communicated in a detailed and timely manner. • Sponsors had greater visibility of project progress and risks. • Crossrail Ltd had greater access to decision-makers, and sponsors had greater access to source information. • Crossrail Ltd developed a more open approach with the public and the sponsors. • Opportunity for robust challenge by P Rep and sponsors.

Themes	Changes implemented in 2018 and 2019	Impacts of changes
 **Skills and capability**	• Sponsors appointed an independent Sponsor Board member and a Technical Advisor. • New and additional Independent Non-Executive Directors, with relevant expertise, were appointed to the Crossrail Ltd Board. • P Rep was strengthened with the expectation that they: voice their concerns; support sponsors in challenging Crossrail Ltd; and express their view of possible schedule and cost outturn when key project risks were identified.	• The sponsors had the confidence that the Crossrail Ltd Board and leadership had the right skills and capability in place to drive delivery and deal with the complexity of the project. • Reviews of project performance and status were more realistic.
 **Project controls**	• Crossrail Ltd established a 'Three Lines of Defence' model of assurance consisting of: 1) programme delivery controls; 2) objective programme assurance; and 3) independent assurance, forming the basis of its Independent Audit and Assurance Plan. • Crossrail Ltd reinstated risk, planning and control functions and identified appropriate independent advisors. • Crossrail Ltd identified an enhanced reporting approach that included the Crossrail Ltd Board report (four-weekly), dashboards (weekly) and the visual management process (daily to weekly). This approach allowed the available material to be adapted as needed for the target audience, and used as a tool for both management and engagement. • The schedule baseline was rebuilt with a focus on the Earliest Opening Programme that identified a six-month opening window. This was informed by engaging with the supply chain in a collaborative manner, undertaking deep dives to ensure remaining scope was fully understood.	• Reporting of cost and schedule forecasts was more realistic and timelier. • The identification, management and reporting of risks, issues and mitigations was improved. • Open engagement on status of programme.

Following the implementation of the changes, the project was subjected to extensive external scrutiny, including:

- National Audit Office (NAO) (2019) *Completing Crossrail* (link: https://www.nao.org.uk/reports/crossrail)
- Public Accounts Committee (PAC) (2019) (link: https://committees.parliament.uk/work/1304/crossrail-a-progress-update/)
- London Assembly Transport Committee (LATC) (2019) *Derailed*: *Getting Crossrail back on track* (link: https://www.london.gov.uk/about-us/london-assembly/london-assembly-publications/crossrail-delay-report)

DfT and IPA also published a report titled *Lessons from transport for the sponsorship of major projects* (link: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/796294/dft-review-of-lessons.pdf) that identified 24 lessons from major programmes. The review was conducted in response to issues encountered in major projects sponsored by DfT, including the 2018 delays announced on Crossrail.

The findings and recommendations from these reviews covered the same themes identified above, and provided reassurance that the interventions to the governance arrangements were required to complete the Crossrail project and deliver a safe and reliable railway.

The reviews also reinforced the need to keep governance arrangements under review so that they remain fit for purpose throughout the project life cycle to recognise the evolving needs and priorities. For example, the remaining delivery stage of the Crossrail project included significant construction activities before progressing through testing, Trial Running and Trial Operations between 2018 and opening the railway to the public in May 2022.

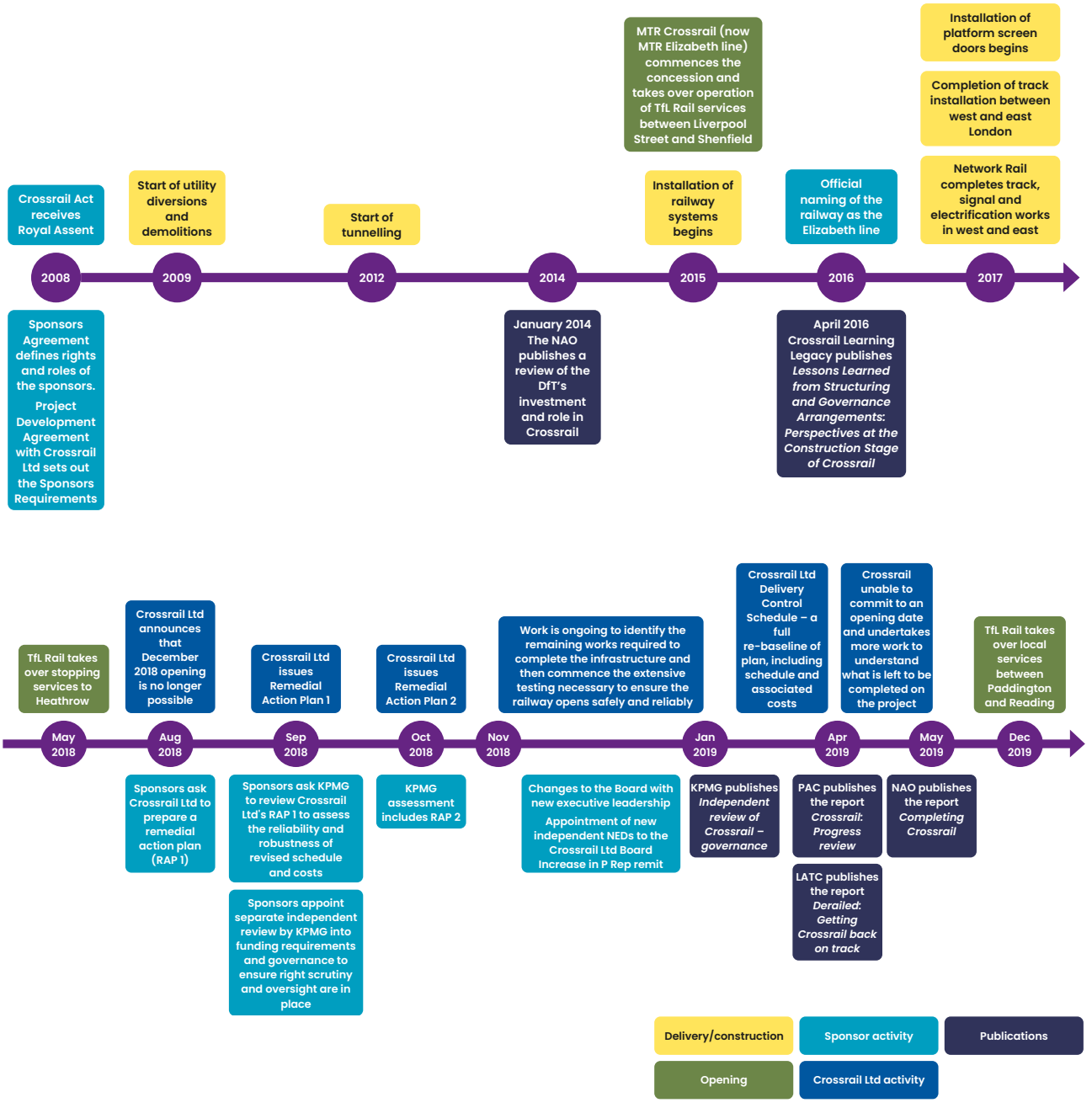


Figure 2 Crossrail timeline 2008–2019

5 Operational pull – further governance changes

In early 2020 the project was focused on commencing intensive operational testing of the integrated railway, having made good progress on finishing the tunnel and track works, and with most stations nearing completion. To support the transition from project delivery into operational readiness, the sponsors identified the need to develop a plan to evolve and adapt the governance arrangements.

As the changes to governance were being considered, Crossrail Ltd identified, in summer 2020, that more time would be needed to deliver the full railway and that the Central Section between Paddington and Abbey Wood would be ready to open in the first half of 2022. There was a strong desire to avoid further delays and ensure appropriate support during the COVID-19 pandemic. Plans were developed to support the delivery and 'pull' the railway into operations. This involved the transition of the governance of the Crossrail project to TfL – the owner and long-term operator of Elizabeth line services, which was in the best position to consider the trade-offs and drive progress to bring the railway into operation. These changes ensured that the governance arrangements remained fit for purpose and became an integral part of the operating organisation.

The three key changes resulting from the governance transition in 2020 were:

- Crossrail Ltd Board replaced by the Elizabeth Line Committee, a newly established Special Purpose Committee of the TfL Board chaired by a TfL Board member, to provide high-level oversight of the Crossrail project, and which DfT attended.
- The Sponsor Board and Elizabeth Line Readiness Group replaced by the Elizabeth Line Delivery Group, to bring together the key TfL executives responsible for bringing the Elizabeth line into operation.
- The separate Crossrail Ltd Remuneration, Audit and Investment committees removed and aligned with those that existed within TfL.

The sponsors also reflected on the respective interests of TfL and DfT when identifying appropriate governance arrangements including a shared interest in cost stability and control.

TfL interests	DfT interests
• Opening a safe and reliable railway as soon as possible • Receiving operatable and maintainable systems and assets • Reputation to deliver major infrastructure • Financial sustainability • Benefits realisation and evaluation of impacts	• Observing obligations in Sponsors Agreement and Project Development Agreement • Delivery against Sponsors Requirements • Protecting public investment • Service integration with National Rail Network • Impact on areas outside London and across the UK • Benefits realisation and evaluation of impacts

The main purpose of the governance transition was to simplify the decision-making process at the executive layer and Board level with no fundamental changes imposed to the project management layers. The changes also ensured that decision making would be fully aligned during the critical final phases of the project as operational testing was undertaken, and the remaining parts of the railway were completed and transferred to operational teams.

Following the governance transition, DfT retained joint decision-making authority for changes to the high-level objectives of the project, as well as accountability for the delivery and realisation of the wider benefits. DfT's role in funding the project, including funding the works being delivered by Network Rail, remained unchanged. While DfT continued to be updated on changes to scope, schedule and cost, and had accountability for reporting progress to ministers, the TfL Commissioner took personal accountability for the delivery of the railway. The TfL Commissioner publicly committed to no further slippage and no further need for public funding beyond what had previously been set by the outgoing Crossrail Ltd Board.

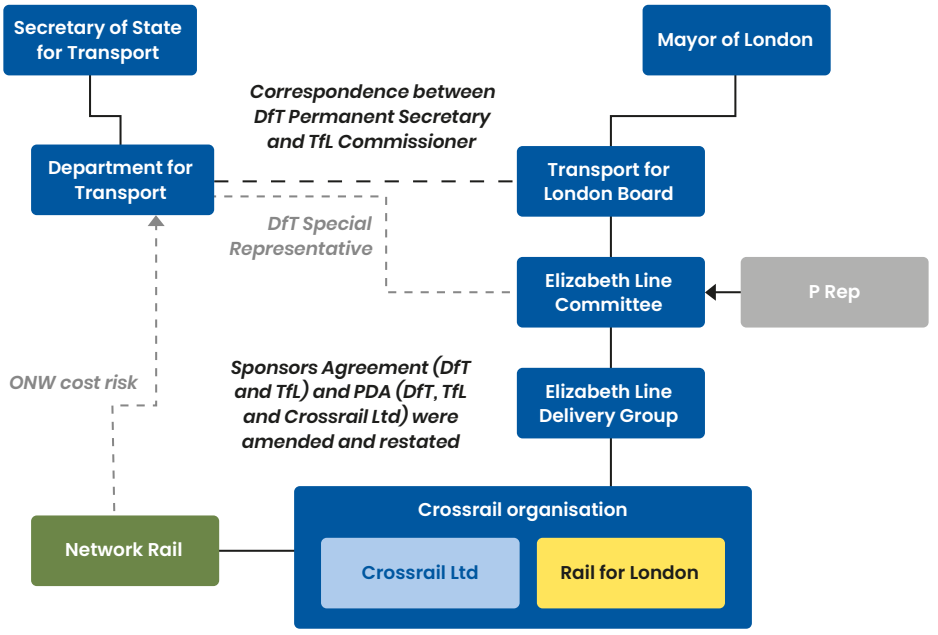


Figure 3 Crossrail governance arrangements post-October 2020

At the time, further external reviews were carried out, following on from the previous enquiries that provided further recommendations to consider:

- NAO (2021) *Crossrail – a progress update* (link: https://www.nao.org.uk/reports/crossrail-progress-update/)
- PAC (2021) *Crossrail: A progress update* (link: https://committees.parliament.uk/work/1304/crossrail-a-progress-update/)
- LATC (2021) *Crossrail: Light at the end of the tunnel?* (link: https://www.london.gov.uk/about-us/london-assembly/london-assembly-publications/forensic-focus-needed-get-crossrail-track)

The NAO review reinforced that it was appropriate for sponsors to amend the governance and oversight arrangements to reflect the stage of the project, and that the changes would help support the project to completion by ensuring that the eventual operators and maintainers of the Elizabeth line worked more closely with Crossrail Ltd. The review also emphasised that to work effectively, particularly as the pressure to open the line increased, roles and responsibilities and how the organisations work together needed to be clear and supported with robust management information and a culture of transparency. Clear roles and responsibilities were also emphasised in the LATC review along with the need to continue to adapt the governance arrangements as the project evolved and transitioned to a fully operational line.

The changes and impacts are summarised in the following table against the themes previously identified:

Themes	Changes implemented in 2020	Impacts of changes

 **Accountability**	• DfT wrote to the TfL Commissioner to formally set out the agreed governance changes and clarify accountabilities, roles and responsibilities, and new ways of working.
	• The TfL Commissioner was made formally accountable for the delivery of the railway.
	• Crossrail Ltd's Chief Executive Officer (CEO) began to report directly to the TfL Commissioner on regular day-to-day management of the project's cost and schedule.
	• The Crossrail Ltd Board, Sponsor Board and Elizabeth Line Readiness Group were replaced by:
	  • Elizabeth Line Committee (ELC) (committee of the TfL Board) to simplify decision making and provide assurance and oversight for the TfL Board on the completion and close-out of the Crossrail project and the opening of the Elizabeth line.
	  • Elizabeth Line Delivery Group (ELDG) to deliver the earliest safe, cost-effective opening date for the Elizabeth line and to take whatever proactive and remedial action was necessary to achieve that goal.
		• TfL was able to provide more effective management focus and effort, to 'pull' the Elizabeth line into operation.
		• TfL, as the long-term operator of the railway, had greater control over the project to bring the line into operation as quickly as possible.
		• DfT approval remained on matters relating to the core agreements and Sponsors Requirements.

 **Behaviours and relationships**	• Visibility of the Crossrail leadership team became a key priority of the TfL Commissioner with daily calls (including over the weekend) between the TfL Commissioner and Crossrail Ltd's CEO, with the Chief Operating Officer, Chief Maintenance Officer, Project Delivery Chief and Programme Manager included as appropriate. • Close relationships between the respective TfL and DfT sponsor teams were maintained, and appropriate processes identified to ensure updates could be provided and risks escalated. • There was a commitment to close engagement with the leadership of key train and signalling suppliers.	• A culture of transparency and openness was encouraged and sustained at all levels of the Crossrail organisation. • TfL was able to pivot towards prioritising the completion of the Elizabeth line with support from across the organisation. • As decision-makers were working together side by side, it was easier to agree trade-offs and drive the railway to completion.

 **Openness and transparency**	• Commitment to a high level of transparency was maintained including:
	  • Publication of ELC papers and ELDG minutes.
	  • ELC meetings held in public.
	  • DfT given visibility of all ELC and ELDG material with a special representative attending ELC and regular updates to DfT Investment Committees.
	  • Monthly updates to the London Assembly Transport Committee and twice-yearly updates to the Public Accounts Committee.
	  • Continued publication of P Rep reports and the responses from the Crossrail organisation.
		• The establishment of trust allowed the project team to focus on delivery (establish processes and then stick with them) and protect against abundant review, a variety of inputs and unnecessary intrusion.
		• Collaborative meetings were held across organisations, including supply chain forums, and integrated schedule and cost reviews held on a periodic basis for full transparency.

Themes	Changes implemented in 2020	Impacts of changes
 **Skills and capability**	• Membership of ELC and ELDG was regularly reviewed to ensure appropriate representation and skills. • P Rep was retained and provided updates as required while continuing to report to sponsors. • Independent advisors were identified to provide assurance during the remaining stages of the project. • Many of the professional services required to complete the project were transferred into TfL with an ongoing role to support operations.	• TfL was able to work more autonomously to make the necessary decisions to drive the project towards opening an operational railway. • A working culture was developed that balanced optimism, to keep the project team motivated, against pragmatism, with more reliable communication of risk, productivity and project performance.
 **Project controls**	• The Operations team increased its contribution to management reports and governance reports. • The TfL Commissioner was asked (along with the Mayor of London, when invited) to attend performance meetings with ministers to report on progress on the Crossrail project. • The TfL Commissioner was asked to attend the DfT Investment, Portfolio and Delivery Committee on a quarterly basis to provide updates on progress. • The Crossrail organisation produced weekly dashboard reports to provide updates on key aspects and metrics of project delivery. • Countdown tactical meetings began to be held every week with the Crossrail leadership team, for concerns to be raised and corrective action taken as necessary.	• More consistent, clear, speedy and effective decision making supported the completion of the Elizabeth line. • An increased level of support allowed for quick and more transparent escalations.

6 Looking to close

Following the governance transition in 2020, key testing, commissioning and handover milestones were met, and on 24 May 2022 the Elizabeth line was successfully opened within the established opening window of the first half of 2022. As planned, Bond Street station opened later in the year on 24 October 2022 and on 6 November 2022, direct Elizabeth line services into central London from Reading, Heathrow and Shenfield were introduced, and the full end-to-end timetable is set to be introduced in May 2023.

To support the remaining activities to deliver the full end-to-end railway and close the project, we are reviewing how to transition the project governance arrangements as risks continue to be retired and the established TfL operational and maintenance processes become more applicable for the management of the railway.

Significant delivery risks were retired with the opening of the Central Section of the railway in May 2022 and the introduction of through services between the Central Section and the eastern and western routes in November 2022. In response, the P Rep was demobilised in June 2022 and remains on a call-off arrangement to provide advice as required and support sponsor-led reviews where appropriate. Project and independent assurance have continued to be provided by the project and independent assurance teams.

We anticipate that the remit of ELC and ELDG will naturally scale back with an eventual end and transferring of residual functions to existing established committees of the TfL Board.

Ongoing sponsor activities that remain for both DfT and TfL include contributing to the benefits management and post-opening evaluation workstreams that are outlined in TfL's benefits framework (*Elizabeth line: Evidencing the value*, link: https://tfl.gov.uk/corporate/publications-and-reports/elizabeth-line-benefits-framework).

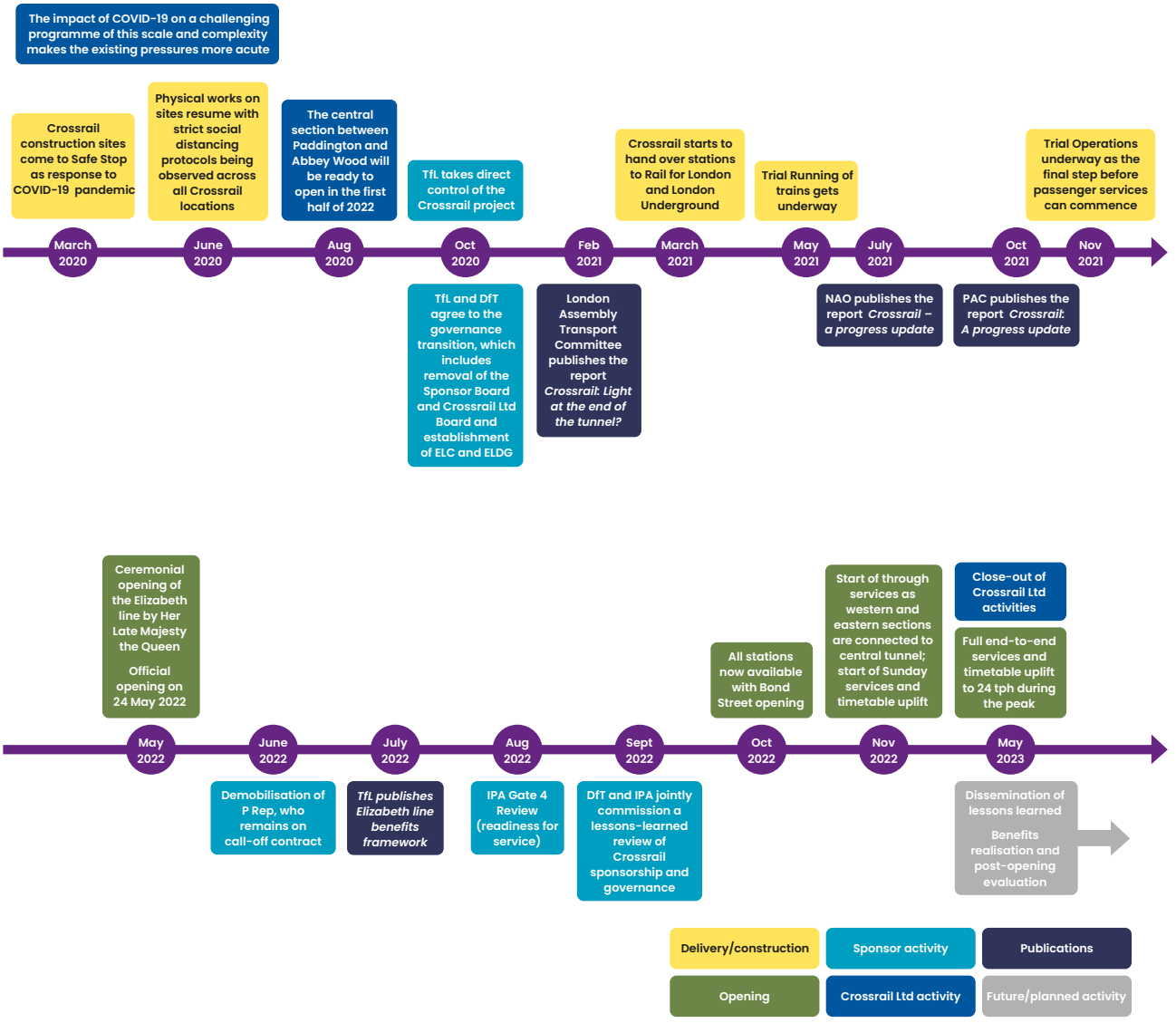


Figure 4 Crossrail timeline 2020–2023+

7 Lessons learned

Reflecting on the key themes and the changes made to the governance arrangements of the Crossrail project from 2018, we have identified the following lessons that may be applicable to other infrastructure projects and programmes with many organisational interfaces over a long period of time.

1. ***Consider adapting processes and relationships before changing existing governance arrangements.***

A key theme from the recommendations has been to ensure that governance arrangements remain fit for purpose as the project progresses. The sponsors kept this in mind and were careful to avoid adding additional pressure to the project when introducing change. Sponsor support for a project includes protecting the delivery environment from unnecessary change and distraction.

Focusing on the desired impacts of aligning processes and behaviours was initially successful in 2019 to reset the project and refresh priorities and behaviours. This provided stability at an uncertain time by maintaining separation between the sponsor and delivery organisations. It preserved the autonomy of Crossrail Ltd, allowing it to rebuild its approach to delivering the remaining activities to introduce the end-to-end railway as soon as possible, while enhancing sponsors' support and oversight to provide confidence in the new delivery team.

On major projects and programmes, governance arrangements will be established early on and codified to reflect assumptions about how the project or programme will unfold. Sponsors cannot predict the future and need to be open to reflect how their interpretation may need to evolve over the delivery life cycle. This evolution does not mean that the governance arrangements need to be replaced – rather that jointly the parties agree to revise processes and relationships, or refresh membership and terms of reference of existing meetings to reflect current risks, challenges and priorities.

Governance arrangements were not structurally changed until interests significantly evolved and accountabilities needed to be refreshed. The arrangements to modify the sponsorship model and bring TfL and Crossrail Ltd closer together were not implemented until TfL could support the remaining delivery of the project and DfT was content transferring control to the TfL Commissioner.

2. ***Identify desired impacts of governance changes to align arrangement with the sponsor's interests in addition to the needs of the project.***

Changes to the governance arrangements should be identified on the basis of the desired impacts the changes will achieve, and monitored to ensure that the intervention was appropriate and check whether further adjustment is required.

The changes should be identified to align with the interests of the sponsor and reflect the risks applicable to the sponsor organisation(s). This will ensure that there is appropriate oversight aligned to the priorities of the accountable organisation(s) to provide confidence that risks are being managed to meet delivery and cost commitments and ultimately deliver the intended outcomes of the investment.

The needs of the project should also be considered to ensure that the governance arrangements support rather than burden the delivery teams. A common purpose should be established where both sponsor and delivery teams benefit from the material produced to support the discussions at the meetings. It is a collaboration between teams, not a hierarchy. Encouraging a culture of transparency will avoid separate management and sponsor reports, and ensure consistency and timeliness in delivering key messages. For the Crossrail organisation, this removed some duplication of tasks and freed up management and administrative time.

Giving sponsors more direct access into the delivery organisation helped to rebuild trust in the delivery team, and over time actually provided more freedom and space for the teams to deliver as sponsor confidence increased. The enhanced access to information also meant that sponsors were in more of an informed position to support the project with escalations with the supply chain and stakeholders.

The need for changes can be considered based on event triggers or time triggers, and either may be appropriate given the situation of the project. What is important is that governance arrangements are kept current, fit for purpose and applicable to both sponsor and delivery teams/organisations.

3. ***The operation of a joint sponsorship model requires review and adjustment as working arrangements and interests change.***

A joint sponsorship model was identified for the Crossrail project to ensure that the interests of the main sponsoring and funding organisations were reflected in the development of the project. A Joint Sponsor team was created to service the needs of both TfL and DfT and to work collaboratively across organisations to meet the needs of both. As organisational interests evolved with the delivery of the project and the completion of the railway approaching, the joint sponsorship model was challenged as different priorities emerged.

Although the joint sponsorship model was replaced in 2020 with two separate sponsorship teams, strong relationships remained to ensure visibility of priorities, interests and risks. Sponsors focused on instilling the right behaviours and culture within and between the two organisations and recognised that with the closure of the Sponsor Board, there was a need to find a new way to work together to support the remaining delivery of the project.

Common areas were identified where the two sponsorship teams could continue to support each other, including public engagement, assurance reviews, completion certificates, lessons learned and benefits management. Where interests were different, additional effort was required to clearly communicate respective priorities so that engagement occurred at the appropriate levels in the organisation and processes were implemented to ensure that needs were met.

Trust between sponsorship teams was important to establish and maintain, as was regular engagement between the organisational counterparts.

The sponsors were also careful to maintain consistency in approach as changes in personnel occurred, both within the project delivery teams and within the sponsorship organisations. In some instances, as teams have become smaller, roles have been combined, and being flexible with available resources has been important given the challenges of recruiting at the tail end of a project.

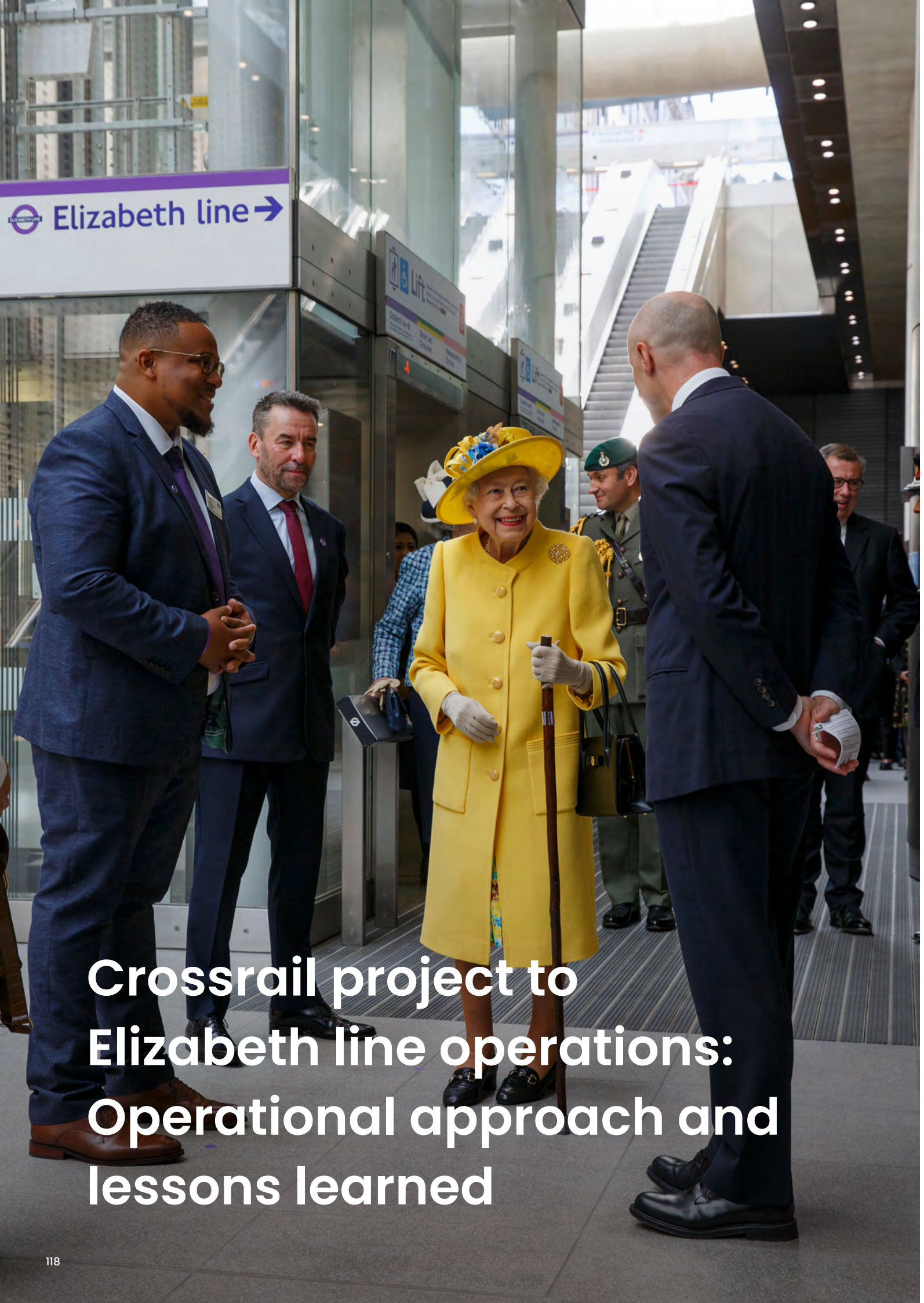
Sharing knowledge across the teams and having the right culture and behaviours in place was helpful for individuals to respond and support workstreams outside their own area. This remains essential to ensure the remaining delivery scope and project close-out activities can be completed successfully and in a timely way.

Relevant learning legacy papers

- Lessons learned from structuring and governance arrangements perspectives at the construction stage of Crossrail (link: https://learninglegacy.crossrail.co.uk/documents/lessons-learned-from-structuring-and-governance-arrangements-perspectives-at-the-construction-stage-of-crossrail/)
- Crossrail programme organisation management delivering London's Elizabeth line (link: https://learninglegacy.crossrail.co.uk/documents/crossrail-programme-organisation-management-delivering-londons-elizabeth-line/)
- Crossrail programme governance (link: https://learninglegacy.crossrail.co.uk/documents/crossrail-programme-governance/)

Relevant published good practice

- IPA Project Routemap – Governance module (link: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1080238/Governance_-_FINAL.pdf)
- APM Governance of Co-Owned Projects (link: https://www.apm.org.uk/book-shop/governance-of-co-owned-projects/)



Crossrail project to Elizabeth line operations: Operational approach and lessons learned

Prologue

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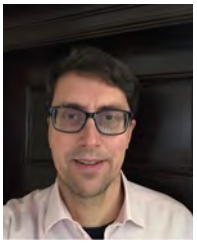

Martin Stuckey

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This paper has been written from the Elizabeth line/Crossrail Operations team perspective – the Operations team role is to act as the guiding mind and focus to bring into use and operate the Elizabeth line, liaising with the delivery teams and other operators (e.g. Network Rail, MTREL – the Crossrail train operating concessionaire, London Underground) for operation of the new line.

While the operator's involvement – and the main focus of this paper – particularly came to the fore in the final one to two years before opening of the line in May 2022, the paper also comments on the vital but less resource-intensive activities of the Operations team during the much earlier planning and delivery phases of the programme.

This paper starts by introducing the context for operating the Elizabeth line, then describes the strategic lessons that are considered the key operational learnings from the experience of bringing the Elizabeth line into use, and which are recommended to other operators and delivery organisations developing new rail schemes. The main section of the report is broken down into the key activities of the Operations team and explains the approach that was taken and what was done, linking this to one or more of the strategic learnings. The paper ends with a concluding note.

Introduction

The delivery of Elizabeth line operations from concept to passenger service has ultimately been very successful. The line is a new type of service in the UK, analogous to the French RER or German S-Bahn systems, and brings together (i) major new infrastructure, (ii) new rules and regulations (as it is a unique railway) and (iii) new teams, many of which are themselves new to the industry and/or are part of organisations that have not worked together in a similar formation before. This is almost unprecedented: most new railways involve one or two of these three elements, not all at once. The Elizabeth line was also delivered within the complex UK/EU-prescribed contractual framework, including separation of track and train.

Nevertheless, the Elizabeth line has (by the end of 2022) delivered almost exactly the train service envisaged in the original Sponsors Requirements and at the time of the Crossrail Bill receiving Royal Assent – with the final stage to follow in May 2023. Change to the proposed service has been carefully controlled throughout that period of nearly 15 years within an environment that could have seen significant and damaging ad-hoc adjustments, with the one significant change being the very worthwhile extension of the western terminus to Reading. Initial passenger operations in the Crossrail Central Operating Section (CCOS) from May 2022 were successful in terms of reliability and attracting ridership – the 'stand-alone' railway that was operated from May to November 2022 was among the UK's most reliable – and while through running onto infrastructure managed by Network Rail (NR) is more technically challenging, there is every sign that this too will settle down into a reliable and very popular service, delivering the benefits intended.

Figure 1

Summary

We have identified seven strategic lessons that have led to successful operations for the Elizabeth line. These are summarised below, with more detailed points set out under 12 workstream headings in the main body of this paper and referenced to the relevant strategic learning (SL1, SL2, etc.).

Strategic lesson 1. Establish and maintain a consistent and coherent vision and specification of requirements based on operational outcomes and customer needs.

The requirements for the operating railway were set out in various formal documents (the Crossrail Act, Sponsors Requirements, Crossrail Programme Functional Requirements and Track Access Option) that applied to the delivery of the project and secured the timetable for operation. Changes to these were rigorously controlled.

Strategic lesson 2. Relentlessly focus on the most important factors for customers and operational staff – ensuring the 'product' is safe and reliable.

Long experience and TfL's own research shows that without safety and reliability you will never achieve high customer satisfaction. With it, you are most of the way there and you can focus more easily on the other elements that really help hit the heights. Ensuring that the product was safe and reliable was consistently repeated throughout all delivery phases over the many years to the various personnel in the delivery organisation and its suppliers.

Strategic lesson 3. Learn from best practice.

The Operations team drew on a range of resources, networks and knowledge to inform the requirements (referred to in point 1 above), the specification of the Crossrail Train Operating Concession (CTOC) and the implementation phase. Many aspects were informed by Transport for London's (TfL's) significant operational experience, including the introduction of London Overground services as well as TfL's membership/formation of the suburban railway benchmarking group with Imperial College London. Independent advisors with expertise in various operational aspects were also drawn on throughout the delivery and implementation phases.

Strategic lesson 4. Have the right team.

The operational team was established to actually operate the railway rather than just 'shadow operate'. This resulted in more continuity within the Operations team than almost any other part of the project – despite the delays to opening – as people joining the team had their eyes on operating the railway. The team members were appointed on their operational contracts under TfL, which mitigated transition risks in relation to a delivery organisation not having to transfer the Operations team to TfL at the end of the programme.

Strategic lesson 5. Ensure everyone has 'skin in the game' and can adapt – the Elizabeth line was a very complex project to bring into use.

As noted in the very first paragraph of this paper, the introduction of the Elizabeth line presented significant challenges and complexity, which were not, or could not be, fully mitigated for at the outset. The ability and capacity to respond to issues that arose was a key factor for operational activities in three areas in particular.

- For the two key operational contracts (CTOC and rolling stock and depot), long-term views were taken in their specification, which supported both suppliers being able to take a longer-term view to work with TfL to overcome issues that arose (e.g. in support of adapting the opening strategy to mitigate delays to customer and revenue benefits from the 2018 delays).

- Rail for London Infrastructure (RfLI) operations and maintenance resources were appointed in readiness for a 2018 opening. The delays then and afterwards, as well as the uncertainty over the actual opening date, resulted in loss of staff/competence due to a lack of flexible options to redeploy staff for the interim period until opening.
- Flexible resourcing contracts were in place and proved invaluable to supplement resources (and cover vacancies) to overcome the issues that arose and to provide resilience for opening.

Strategic lesson 6. Ensure there is sufficient time and capacity to learn and familiarise personnel prior to opening the railway to passenger use.

Trial Running and Trial Operations were always the planned final phases before opening the CCOS to customers, and these provided the opportunity to demonstrate that the railway would be reliable and for staff to undertake various exercises to ensure that passengers would be safe. It ultimately took 14 months from the start of Trial Running until passenger service (although this period was significantly disrupted by various blockades to complete work on the railway), which provided the opportunity to undertake tests, trials and exercises. There were very detailed plans about what would be done each day during this period, but the goal for the period ultimately was for operational (and maintenance) personnel to develop confidence in the assets, the railway system as a whole, the processes used and their colleagues. This was so that appropriate actions and responses to situations could be taken without prolonged consideration. As the period of Trial Operations evolved, it became increasingly apparent that the building of confidence could not be prescriptively scheduled, nor was it a linear process, and as such the focus increasingly turned to identifying learnings collectively and replanning accordingly.

Strategic lesson 7. Collaborate with delivery activities and personnel, and lead the bringing-into-use phase.

There was always an operational presence within the delivery organisation – which was essential from the start – and this creates a tension: "have built it / finished, I am now leaving" by delivery folk versus "but you haven't given me everything I want" from operators. It became increasingly apparent after 2018 that there would be no success for any party unless the railway worked and would be safe and reliable. It was also then obvious that the 'big bang' approach to opening that had been pursued up to 2018 would lead to the highest cost and longest timescales to implement, and thus a pragmatic approach was required. This involved a change of mindset and collaboration between all parties and a clear understanding that we sank or swam together - 'owning the whole'. This was not a quickly won change, and interestingly the pandemic – while creating a range of significant new challenges – proved a bit of a boost to achieving this change of mindset.

The final aspect of working within and with the delivery organisation is that at some point operations needs to take the lead – but not so soon that there is a 'tail' of delivery activity that operators are not suited to implement, or which requires significant access (and blockades/closures).

Operational workstreams

1 **Establishing clear operational requirements that deliver to the needs of sponsors and customers**

Sponsor requirements were written by an operator, who then played a progressively more important role in the implementation of the project. The requirements were written as outcome based and were formally set for the project. They stood the test of time, although interpretation as to how they could be delivered required strong operational influence in the design/delivery phase. (SL1)

The service pattern, with a limited number of branches and a defined geographical extent, was set (with operator input) before the bill stage. This was a vital foundation and meant that timetables and the customer proposition could be developed on a coherent basis. It's worth noting the Elizabeth line closely resembles French RER or German S-Bahn systems in mixing suburban and core metro operations, and this philosophy – and geography – has been maintained throughout, from design to passenger service. (SL1, SL2, SL3)

To ensure that the huge investment in the Central Operating Section (CCOS) could be used as anticipated, TfL worked with DfT and was granted 30-year rights (the 'Track Access Option') for operating the Elizabeth line and transfer of parts of the Greater Anglia (GA) and Great Western franchises. This not only provided certainty but also had the benefit of defining early and very clearly the service pattern that would be provided, and thus a sound basis for planning the remaining elements of the project and also other operators' services complementing the Elizabeth line. (SL1, SL2)

The Operations team, working within the delivery organisation, defined the customer proposition and successfully brought forward (albeit a relatively small number of) initiatives to cover key gaps from a customer perspective that were identified after the Crossrail Act was approved and which were not in the original Sponsors Requirements. Delivering these outside the Crossrail (CRL) delivery organisation avoided the difficulties of increasing the scope of a programme in delivery, but required additional capability and funding that was progressed by the Operations team. (SL1, SL2, SL3, SL5)

- On-Network Station Improvement Programme, which delivered consistent minimum standards end to end and a line-wide TfL identity, as well as delivering step-free access at the seven stations that would otherwise have not been step free.
- Liverpool Street mainline station platform extensions, without which there would have been little or no ability to operate at all with the CCOS closed, and which also enabled the flexibility required for revising the opening phasing to support introduction of through running into the CCOS outside of a timetable change.
- Additional rolling stock to support extensions to Reading, operation of a uniform fleet, and 'hot spares' to support operational reliability (although pre-priced options were included in the rolling stock procurement contract for this eventuality).
- Plumstead maintenance sidings and maintenance depot (which were not included in the original plans, where it was assumed that infrastructure maintenance would be provided from NR depots away from the CCOS).
- Ticket gating to support use of integrated ticketing/Oyster card on stations operated/maintained by other operators.
- 'Red Thread' design activity and application. The establishment of the Crossrail Design Panel, chaired by the Chief Operating Officer (COO) and attended by the Head of Architecture, TfL Head of Design and CRL Board members, provided a valuable focus and coherence to what could have been a fragmented identity.

2 Defining and implementing a strategy for opening and then following it in the light of issues arising, risk and uncertainty

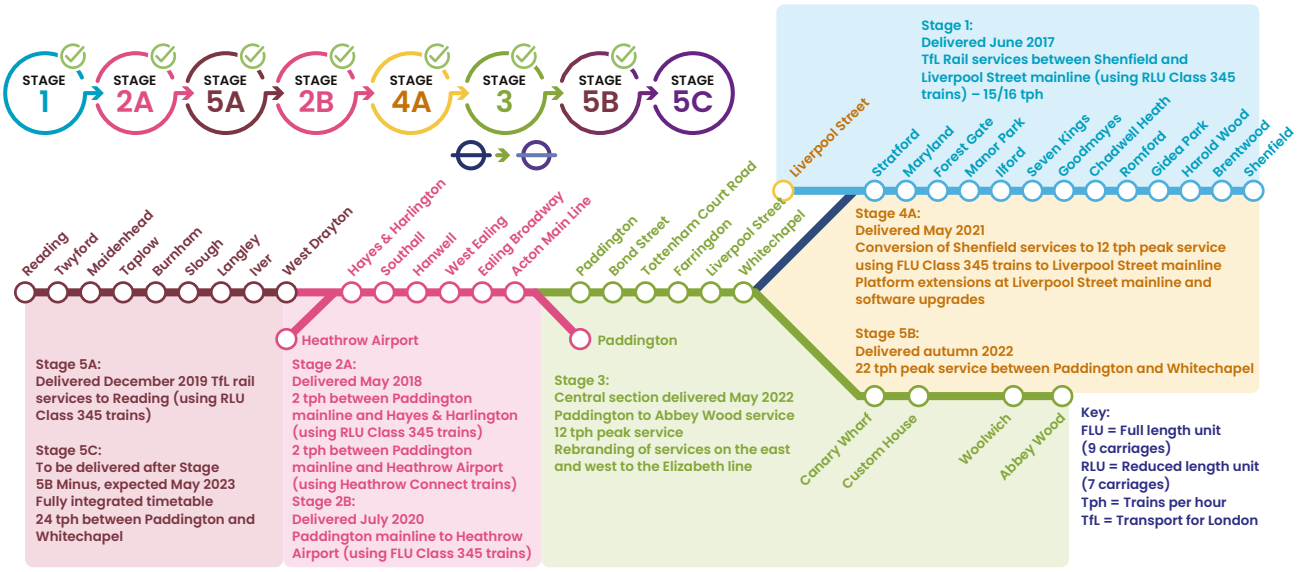

Figure 2

The very significant risks in adopting a 'big bang' approach to opening were avoided by defining a staged opening (which introduced a contracted train operating company early together with phased introduction of rolling stock, initially on the surface railway, and a phased connecting-up of east, central and west routes). (SL2, SL3, SL5)

Customer/revenue-driven focus was key in light of delays that emerged in 2018 to introduce revised phasing with new phases introduced that enabled: (SL1, SL4, SL5)

- extension of operation to Reading, known as Stage 5A, in 2019
- operational resilience and flexibility for future opening stages through platform extensions at Liverpool Street mainline station and timetable reconfigurations, known as Stage 4A, in May 2021
- end-to-end operation (known as Stage 5B Minus) within six months of opening Stage 3 while also achieving flexibility over its precise date outside of national timetable changes (noting that additional considerations were introduced to revising timetables as a result of serious issues with the Thameslink and Northern timetable changes introduced in 2018)

An 'Earliest Opening Programme' was considered following on from the delays announced in 2018 (see also lessons-learned paper on recovery for the delivery perspective). This identified and considered various combinations for opening the CCOS – including how many and which stations would be required as a minimum – and also (briefly) considered passenger operation on only a part of the CCOS. The complexities of the systems in the CCOS ultimately led to the conclusion that these needed prioritising, and the strategy followed was to introduce testing/Trial Running over the whole CCOS, with the stations progressively achieving readiness states that would support through running first. (SL2, SL4, SL5, SL7)

3 **Agreeing the organisational structure and responsibilities for operations and establishing them**

As part of the agreement between government and TfL, it was decided a concession contract would be let for operation of the trains and management of (some) stations using the model successfully established for Overground. It was also agreed that NR would be the Infrastructure Manager (IM) for the CCOS and London Underground (LU) the IM for the five stations that are (very significant) expansions of stations it already operates. (SL3, SL4, SL5).

CRL recommended, and sponsors agreed, to change the IM for the CCOS from NR to RfLI (a new TfL subsidiary organisation) in 2013, to reduce risks associated with acceptance of the CCOS, as NR did not have specialism or focus on metro tunnel operation and maintenance. This required establishment of RfLI as a new organisation with opportunities to set up an organisation from scratch that supported a strong customer focus with its own culture but equally presented challenges to overcome in terms of building expertise and knowledge in parallel with a new set of assets that have no operational/maintenance record (with more details covered under various issues below). (SL2, SL5, SL7)

4 **Defining the rules and processes for operation**

Elizabeth line CCOS operations combines elements of both National Rail (through services mainly on NR tracks, mainline railway trains, 25kV electrification, conventional signalling) and LU (21km of central tunnels, 24 trains per hour (tph), Communications Based Trains Control (CBTC) signalling and platform screen door operation). The philosophy that was adopted was to take the National Rail Rule Book as a base, and the Operations team then worked, very successfully, with the Rail Safety and Standards Board to write the new Rule Book and procedures and manage their acceptance. A similar 'line-wide' approach was taken to the Driver Only Operation (DOO) systems, notably DOO CCTV, where an in-cab leaky feeder-fed system from platform-mounted DOO cameras was needed for the CCOS (because of the use of platform screen doors (PSDs)) but also adopted for the surface stations. (SL2, SL3)

5 **Specifying, procuring and bringing the rolling stock into use, including its maintenance and depot construction**

As the rolling stock contract is a 30-year design, manufacture, maintain arrangement, it made sense for it to be contracted within TfL – the party that would have the long-term relationship. Nevertheless, it had to be closely managed as part of the overall Crossrail delivery project and was therefore integrated into CRL's programme reporting and controls. (SL4, SL5, SL7)

The specification of the train was a complex process but again has very largely stood the test of time. A key challenge was making the train equally suitable for medium-distance suburban/surface 90mph running and metro-style high-capacity/high-frequency running in the CCOS. This has been a challenge to RER/S-Bahn systems, and was achieved in the case of the Elizabeth line by the specification of a regular three double doors per carriage (different to standard UK practice of two sets of doors at 1/3 and 2/3) and also careful design of the interior layout, with wide circulating areas round the doors, a careful mix of longitudinal and 'bay' seating, and physical and visual 'cues' designed to move people away from the door areas. (SL3)

The interior design of the trains was led by TfL in collaboration with the train manufacturer, and with the support of a third-party design agency that helped to deliver a much more considered interior ambience than is traditionally applied to commuter/metro vehicles,

with colours ranging from darker shades at ground level to lighter ceilings, carefully diffused lighting, high-quality stainless steel fittings and careful colour contrasts, meeting the requirements of those with visual impairments but without the heavy use of orange and yellow, which gives many buses and trains a 'climbing frame' ambience. The rolling stock procurement contract included a 'permitted design change' principle that allowed TfL to develop the manufacturer's standard interior designs to deliver a train uniquely tailored to the Elizabeth line. (SL2, SL3)

Consideration was given at specification stage to whether toilets should be provided on trains or on stations. It was decided that on/near-station provision was the best answer, given that these were metro trains with a short average journey length and that toilets would take up significant space within the overall train. Toilets were therefore provided at 34 of the 41 Elizabeth line stations, including virtually all surface stations where longer journeys begin and end. (SL2)

The train is in many respects 'the integrator' of the various CCOS and surface systems, including the three signalling systems (European Train Control System (ETCS), CBTC and 'conventional' Automatic Warning System (TPWS)), the PSDs, radio (GSMR), Supervisory Control and Data Acquisition (SCADA) and power supply.

The procurement exercise was run by CRL to TfL's specification and five parties initially bid, reduced to four (with the withdrawal of Alstom) and then to three (with the withdrawal of Siemens). The competition was won by Bombardier (now Alstom) with the first production of its new 'Aventra' platform. Its train was the most 'track friendly' of the three bids and had the lowest long-term costs. The contractual basis and risk allocation have remained as originally envisaged. (SL7)

The rolling stock and depot build-and-maintain procurement was launched envisaging a PFI-style 'service provision' contract and with manufacturers obtaining financing. After the first round of bidding the sponsors changed to an outright purchase structure and the bid process was rerun. Notwithstanding, CRL delivered contract signature on time in 2014. The train itself was approximately one month late entering service for Stage 1 of the Elizabeth line (June 2017) using conventional signalling (due to train software and regulatory approval delays), and was 18 months late (to the original sponsor requirement) entering service to Heathrow using ETCS signalling. (SL2)

The technical complexity of integrating three signalling systems on the train, and the duration of testing and compatibility-proving needed between the trains and infrastructure systems, presented major challenges to train readiness. This led to the need to prioritise CBTC over ETCS to support the critical CCOS programme. The delays to the CCOS infrastructure and systems meant the train could not be tested in the CCOS in line with the original schedule.

The complexity of the train systems, especially the software controlling the three signalling systems and the overall train control software (TCMS), led to low reliability, which has been successfully mitigated to support entry into passenger service while defects are progressively fixed; although, with a high level of redundancy, most failures can be recovered fairly swiftly by a system 'reset' by the driver. This remains one of the key reliability drivers of the overall railway. (SL2)

A new fleet maintenance depot at Old Oak Common was bundled with the rolling stock procurement. The depot layout and principal features were specified by TfL based on depot operations experience, and the detailed design and construction was carried out by the rolling stock manufacturer and its civil engineering and depot systems subcontractors. The benefits of this process were using the TfL concept design to obtain planning consents in advance of the depot procurement, to de-risk the programme, and a depot design perfectly matched to the maintenance needs of the new trains.

Old Oak Common Depot was brought into use in stages starting in March 2018 and was fully operational by July 2018. This was two months later than the original programme due to sponsors agreeing to temporarily pass a parcel of depot land to NR in connection with the decommissioning of an adjacent railway facility. This required a substantial re-phasing of the new depot construction. (SL5)

6 **Specifying, letting and managing a contract to manage train (and station) operations**

We used the experience and knowledge from management of the London Overground concession, which was let around seven years in advance of the concession for the CTOC – which commenced operating inner GA services from May 2015 (providing a network to facilitate driver training and rolling stock introduction). Key points included: (SL3, SL5)

- No revenue risk. Service delivery-based payments that incentivise delivering reliability, recovering the service (whichever party caused the failure) and a basket of customer satisfaction/revenue indicators.
- Incentivisation to ensure that industrial relations risks are managed and that there are sufficient drivers. The CTOC 'inherited' drivers from previous TOC(s) but needed to build a significantly larger workforce to support the expansion of services for Elizabeth line operation.
- The duration of contract was set for full staged opening (assumed end 2019) of Crossrail plus three years, with further extension option.
- Some flexibility within the contract to vary for provision of minor works – noting that the core operational incentives/obligations in the contract should minimise adverse impacts to operations from doing any works.

7 **Establishing the infrastructure maintenance and operations organisation (Rail for London Infrastructure, RfLI)**

RfLI – a new infrastructure management organisation – was appointed to manage the CCOS, as described in workstream 3 above, which was established from scratch.

The opportunity was taken to try to radically update the operations and maintenance concept compared with existing systems. (SL1, SL3)

Multiskilling was the preferred approach wherever possible and has been more successful within operations than maintenance. (SL5)

In maintenance the approach has been condition-based rather than time-of-failure-based reactive maintenance, using the large amount of data and remote condition monitoring available. However, the asset data has, as on other projects, proved to be the most challenging part of the completion and handover process, and condition-based approaches require an understanding of wear and a maturity of the infrastructure that has not been fully realised to date. (SL3)

One of the most significant changes to maintenance practice compared with existing UK infrastructure managers has been the elimination of Red Zone working and the use of handheld devices that form part of the signalling system to lock out sections of track and take and hand back nightly possessions. (SL3)

Recruited with expectation to train and establish a 'new culture'. (SL3)

Lead time for competency and delays impacted skills retention. (SL5)

Because the CCOS (and RfLI) use a heavily adapted version of the National Rail Rule Book, many competencies differ from their NR or LU equivalents. This imposed a heavy burden in terms of bespoke training and assessment and a difficulty in keeping up competencies. A dedicated training facility was established by repurposing the former Tunnelling and Underground Construction Academy (TUCA). (SL5)

There were also challenges in training in advance of having infrastructure available, requiring the initial group of Traffic Managers (signallers and power controllers) to achieve competency largely on the basis of simulators, and familiarisation of maintainers was only possible quite late in the handover process. (SL5)

Because of slippage to the project timescales (notably the delay announced in 2018), a significant number of staff were taken on earlier than required, leading to skills fade and some leaving before starting their substantive roles. (SL5)

Specialist yellow plant was identified as necessary to enable the maintenance of the CCOS and milling machine, and infrastructure monitoring vehicles were procured that use leading technologies to provide very efficient maintenance and inspection. These are complex tools and required significant effort to integrate and test along with the Class 345 passenger trains. (SL3, SL7)

8 Working with(in) the delivery organisation – role of Operations team – and working with external operational parties

It was helpful that the COO, as the senior operational voice and guiding mind, was appointed reporting to the CRL Chief Executive Officer in 2013 and was a member of the Crossrail Executive team. (SL7)

There will always be tensions between the delivery organisation and the receiver/operator, but these were generally at an acceptable level – although with particular challenges in the period immediately before and after the announcement of the delay in 2018, when there were tensions in almost all relationships within the overall project. After the reset in 2018–2019, things were much more collaborative, and there was a clear focus on meeting the requirements of the Infrastructure Manager and operators and a recognition that the project could only be a success once it was integrated and delivered a high-quality operational railway. (SL7)

Collaborative working with the delivery team led to a number of benefits in terms of being able to take advantage of opportunities arising from its activities (e.g. TUCA was transferred and converted to a wider training facility, storage facilities were created for spares). (SL7)

Operations defined and led a countdown process to Stages 1, 2, 4A, 5A, 3 (from Trial Operations (TO)) and Stages 5B Minus and 5C. This included, for Stage 3, decisions to phase TO into two phases and adding a timetable demonstration phase. Countdown to Stage 3 Trial Running (TR) was led jointly by Delivery and Operations. (SL2, SL5, SL6, SL7)

There were various iterations of governance around the project and operations, but success was driven less by structure than by the relationships and experience of those involved. The senior leadership of the project post-2018 had much greater experience of the integration and commissioning phases of railway projects and the need to bring all parties to a joint success. (SL7)

A Systems and Operations Advisory Panel was established to challenge and advise on scope of operational activity. It was largely helpful and brought external perspectives and experience from other projects, but, like other aspects of Crossrail governance, could lead to repeated discussions of the same issues in a number of different forums and required quite an effort by the executive to provide information and briefings. (SL3, SL7)

Work with other Infrastructure Managers was relatively late to hit its stride, as the project organisation dealt with NR largely through the On-Network Works and RfLI was embryonic for the early part of the project delivery period. NR had many interfaces both in terms of adjoining IM (east and west) and also in terms of timetabling, and provision of national systems such as GSMR – and in its day-to-day relationship with CTOC, which was operating services on the surface sections from May 2015. The IM and operational activity and co-ordination came together from 2020–2021 as day-to-day involvement with NR and LU was increased through testing and then – successfully – through Trial Running and Trial Operations. The fully integrated T-minus countdowns (to commence the next phase) embedded more of a culture of joint endeavour and ownership. (SL4, SL7)

9 Accepting CCOS infrastructure into use

The infrastructure handover approach broke the railway down into 27 elements, so that it was manageable and divisible but in coherent parts that could be integrated and tested. This approach generally worked well. (SL7)

Considerable tension occurred with the initial, precedent-setting, handovers. This was significantly exacerbated as a result of the delays to the programme – where operator personnel involved in acceptance had lost trust in the delivery team as a result of feeling let down and disappointed by cumulative delays in the programme and unmet 'promises' to complete the assets by certain dates. The result was that the bar set for Handover, which included provision of all the records (e.g. asset data, operational and maintenance manuals), meant communication was very transactional. This only changed when both the delivery and operator personnel started to trust each other, which occurred through changes of personnel and the personal drive and willingness to collaborate by some individuals in key positions, as well as the 'reset point' to ways of working, triggered by the pandemic, which catalysed the 'we are all in this together' spirit. Once this collaborative approach was established, it led to achieving 'beneficial use' for a number of the assets whereby operators could become familiar with the assets in practical terms while the records were finalised in parallel to achieve a Handover. (SL2, SL7)

Senior intervention, focused on the overall outcome for TfL, was employed, which also assisted with the possibility of 'star chambers' being used. This helped move things to a conclusion, which was good, as only a fraction of the potential issues could have been handled at that level. (SL7)

Ultimately the receiving parties (RfLI, LU and CTOC) had an effective veto on safety grounds, although the process of commenting on handover documents became very transactional and needed common-sense senior intervention focused on risks to bring it over the line. (SL2)

10 Testing and commissioning the railway

- Running test trains while construction continued.
- Placing a railway into use according to the Office of Rail and Road (ORR) requirements (the Railways and Other Guided Systems Regulations (ROGS)).
- A period of Trial Running including managing access for remaining construction work.
- A period of Trial Operations including operation and emergency exercises using volunteers.

Four months were assumed in the initial plan (firmed up between 2008 and 2010) for commissioning Stage 3 (three months TR and one month TO), which assumed a clean handover of the full railway. In fact, 14 months were required including significant effort to undertake trials, iterate and build reliability in parallel with managing works needed to enable passenger operation. (SL6, SL7)

The Trial Running railway was still very immature and subject to significant technical upgrading and change. A cautious safety-first approach was taken, building up from an initial 4 tph to the full pre-service levels. (SL2, SL6, SL7)

A dedicated team for Trial Operations was established by the Operations team, which paid major dividends, and this team took control of the plan for all activities that were to be undertaken once this phase had commenced. (SL4, SL7)

Trial Operations was, however, conceived of as taking place on a technically and operationally mature system; in practice there was much more learning during Trial Operations. The challenge wasn't so much to invent exercises and create opportunities for rehearsing responses to disruption – the disruption was there 'naturally' at that stage. So, the challenge was then how to avoid overwhelming and burning out new staff and how to share lessons learned effectively, especially with six or seven shifts of staff covering 24/7 operation and partners such as NR and CTOC learning too. (SL5, SL6)

For the countdown between stages, a high-level and high-profile T-minus approach was taken, involving all the key operational parties, at senior manager and director level, and chaired by the CRL Chief Operating Officer in TO. It was used to ensure the receivers were in charge of the process rather than those handing over the railway. This worked well. (SL6, SL7)

The other successful elements of T-minus were keeping it to a sufficiently high level to ensure all areas could be covered at each weekly meeting; clear thresholds, although with a common-sense rather than 'hair trigger' approach to their use; self-declaration by accountable directors rather than 'inquisition'; a 'red is good' approach, where a culture was developed where it was seen as laudable to highlight issues so that help could be offered and plans supported; and an 'own the whole' approach to the product, the 'safe and reliable railway'. (SL3, SL7)

11 Building reliability

The Elizabeth line is an unusual railway in the complexity of predicting and achieving reliability, as it spans significant new infrastructure and trains as well as long mileage on existing and upgraded existing infrastructure, and also has complex transitions between signalling systems. The overall reliability requirements for the CCOS were derived from end-to-end modelling used in supporting the grant of the track access option. (SL2)

These CCOS reliability, availability, maintainability and safety (RAMS) targets were in turn broken down by component systems to build overall reliability. However, elements of the systems were brought into service at different levels of maturity, and the train and signalling suffered particularly from software bugs that took time to resolve given the life cycle for changes to safety-critical 'SIL 2 and above' systems. (SL2)

In addition, the existing infrastructure and services interacting with the Elizabeth line performed differently from those modelled inputs from nearly 10 years before, so the reliability modelling and actions needed to continually be updated and revised. (SL5)

A Reliability Board was created involving all of the key parties involved in operations (CTOC, NR, LU and RfLI as well as the Crossrail project team) and chaired by the COO. The main train and systems suppliers either attended directly (Siemens and Bombardier/ Alstom) or were represented by project managers or engineers. (SL4, SL7)

During Trial Running a weekly Reliability and Resilience Delivery Group was initiated, based on a weekly cycle and focused towards immediate actions to address current issues. (SL7)

A dedicated reliability team was established and was present on a shift basis in the Route Control Centre throughout the mobilisation and initial operating period, providing in-depth analysis, particularly of complex system-related issues such as train and signalling software and platform screen doors. (SL5, SL6)

12 Governance and transition/management into full operation and business as usual

The principle employed was to appoint all business-as-usual (BAU) personnel to their 'home' department/organisation (rather than to a team within the delivery organisation) and promote a collaborative approach with the delivery organisation to collectively bring the railway into use. This established a business-as-usual function in good time for opening (many RfLI personnel were in post by the end of 2017 – some four or five years in advance of the CCOS actually opening, which, of course, created its own problems with staff and skills retention) and ensured no transition was necessary. (SL4)

Similarly, a systems programme was established in 2016 that built the various management systems (e.g. for asset management, competency management) on TfL's IT estate, which again meant no transition of IT systems was required – although the asset information developed by CRL did need to be transferred, which was done progressively as it became available and was finalised. (SL4)

The Operations team worked under the governance of CRL during the delivery phase of the programme, which operated under authority delegated by sponsors. The various directly contracted TfL resources (e.g. RfLI personnel and the contracts for the trains and operating concession) were approved and managed in accordance with TfL's 'business as usual' governance. Working under the delivery organisation provided benefits, as decisions could be made and implemented swiftly, as that is how CRL set itself up; but the interface with TfL-contracted resources did present challenges as pre-2018 CRL tended to perceive these resources as an external supplier rather than people who would actually be operating the railway. This also led to tensions as to what should be funded by CRL and what should be funded by TfL, and sponsors' opinion was sought on a number of occasions as to which was the responsible party. The change in governance in 2020 to TfL managing the programme brought both of these governance routes together and also provided the focus to bring the Elizabeth line into use. (SL7)

A budget was identified and secured for operations activities at the outset of establishing the function within CRL, which was not fully detailed initially but proved essential to enable the team to be built and be able to respond to emerging items and issues. Flexible resource contracts (for project or bringing-into-use purposes) were established to support response to emerging issues and accommodate the issues arising from delivery complexities and delays. Resource contracts and non-BAU personnel for the Operations team were sourced via both CRL and TfL. This added complexity but provided options. Resource management was a vital activity – in terms of mobilising teams as well as responding to issues and risks and adding resilience. It was given a dedicated focus within a business management function with knowledge of and links into both the delivery and operator BAU processes, organisations and personnel. (SL5)

Some contracts were let via TfL rather than CRL. This was the right approach for the major contracts for CTOC and the rolling stock and depot (RSD), as TfL is the owner of the key obligations, costs and revenues associated with them, but it was important that governance of those TfL contracts that had deliverables necessary for CRL's performance was managed day to day within CRL's programme controls (rolling stock being the obvious example for integration and commissioning of the CCOS). (SL4, SL7)

Transition and demobilisation activities were initially led by CRL. (SL4, SL5, SL6)

- In anticipation of a 2018 opening, the demobilisation of staff commenced as early as 2016 for some of the central support functions (e.g. Commercial, Programme Controls).
- During 2020 CRL established a transition workstream – the right thing to do, but principally with too many personnel involved (e.g. external consultants with no previous involvement in the programme) who lacked knowledge of or ownership/accountability within TfL. The transition worked better with fewer people involved, who had a good understanding of TfL and its organisation, and using simplified methods that promoted close interaction between 'givers' and 'receivers' of knowledge, activities or personnel.

It was recognised both that the opening of the Elizabeth line and evolving it to full end-to-end operation were significant changes to manage, and that it would take many months to establish operations truly as 'business as usual'. Additional resources (particularly drawn from personnel already involved in some way within the programme) were deployed to provide a heightened level of resilience in the preparations for these phases, during them, and during their early bedding-in. This also considered the impacts of sickness (COVID-19 still provided a material risk) and more latterly industrial action, which also impacted operations and preparations for Stages 5B Minus and 5C. (SL5, SL6)

Conclusion

This paper has identified seven strategic lessons that are recommended to operators and delivery organisations that are developing, or wish to develop, new rail schemes. It is considered essential that the operational guiding mind is established at the outset. The operator's role is to champion the customer and the operability of the project. The resource-intensive effort of operators is at the end of the project (and beyond for day-to-day operations), but this role is ultimately absolutely critical throughout the whole development and delivery phase of a project if its benefits are to be fully realised.

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