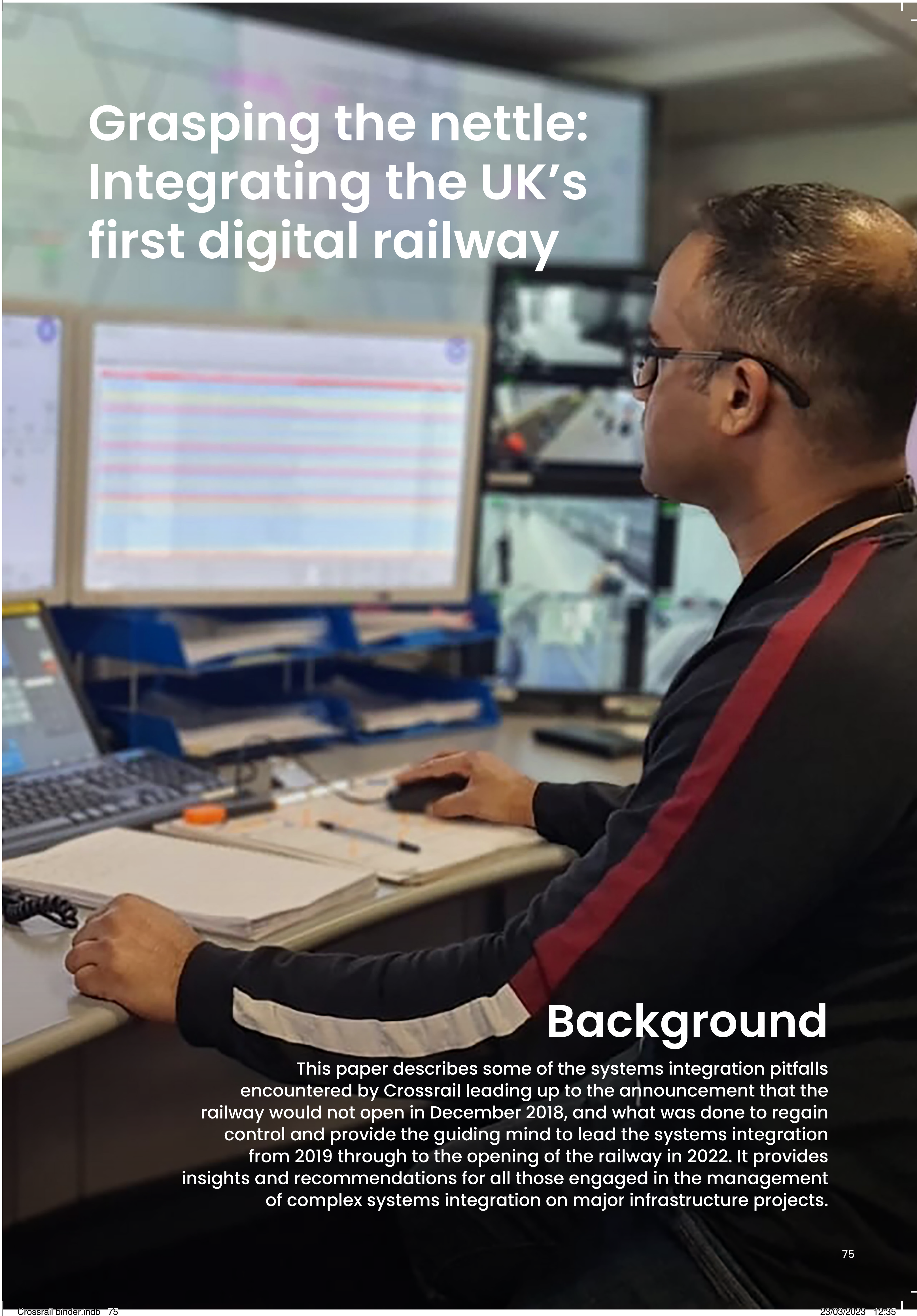
Grasping the nettle: Integrating the UK's first digital railway



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

Author:

Colin Brown

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 Maximising digital technology for a new railway allows outdated working practices to be overhauled and significant savings to be achieved in the full-life operating costs of the network.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.

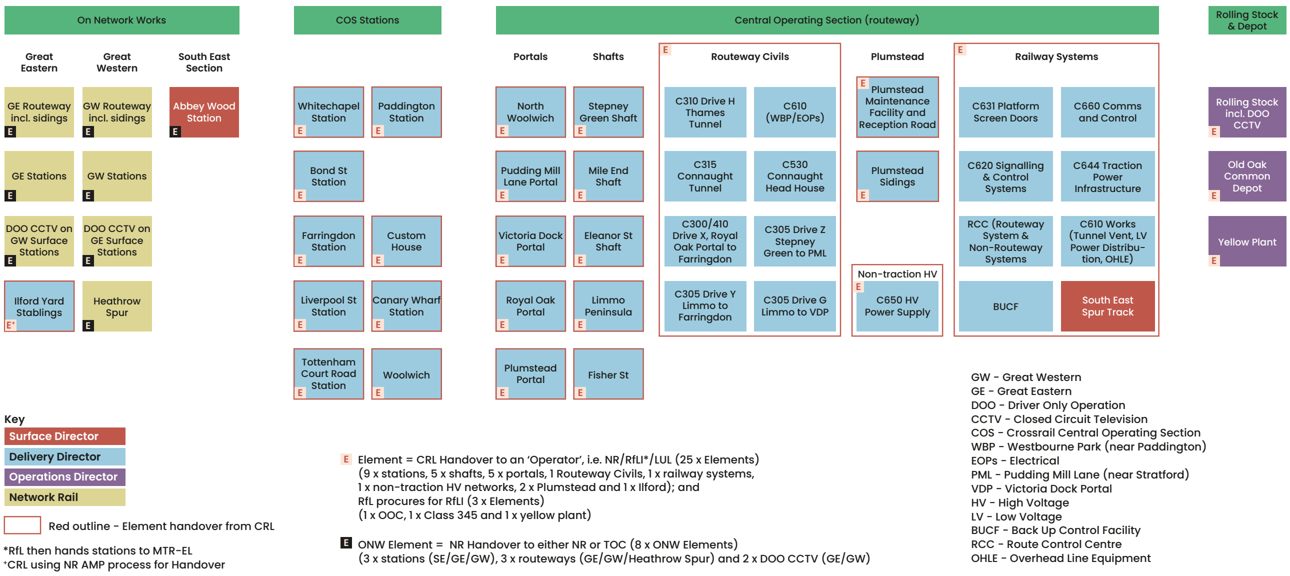


Figure 1 The complexity of size and volume

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.

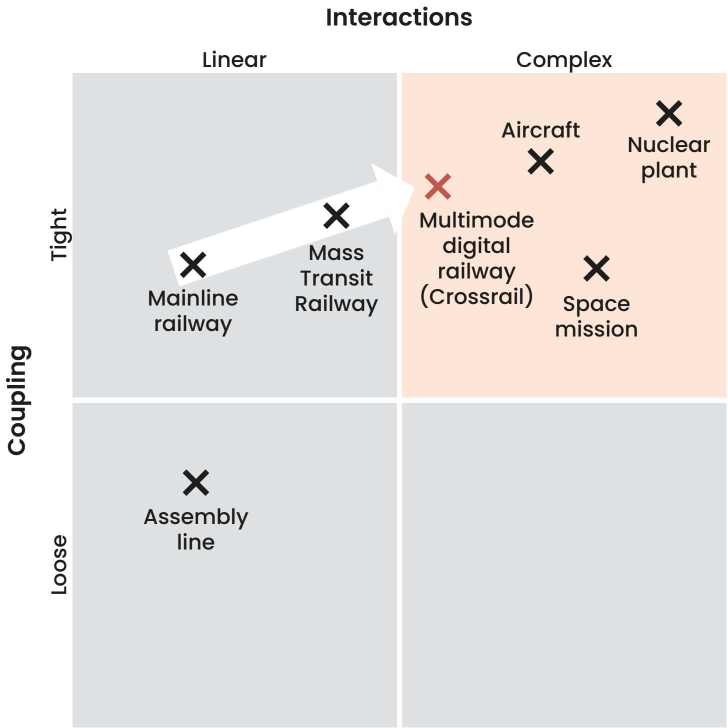


Figure 2 Increasing complexity of coupling of railway systems

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.

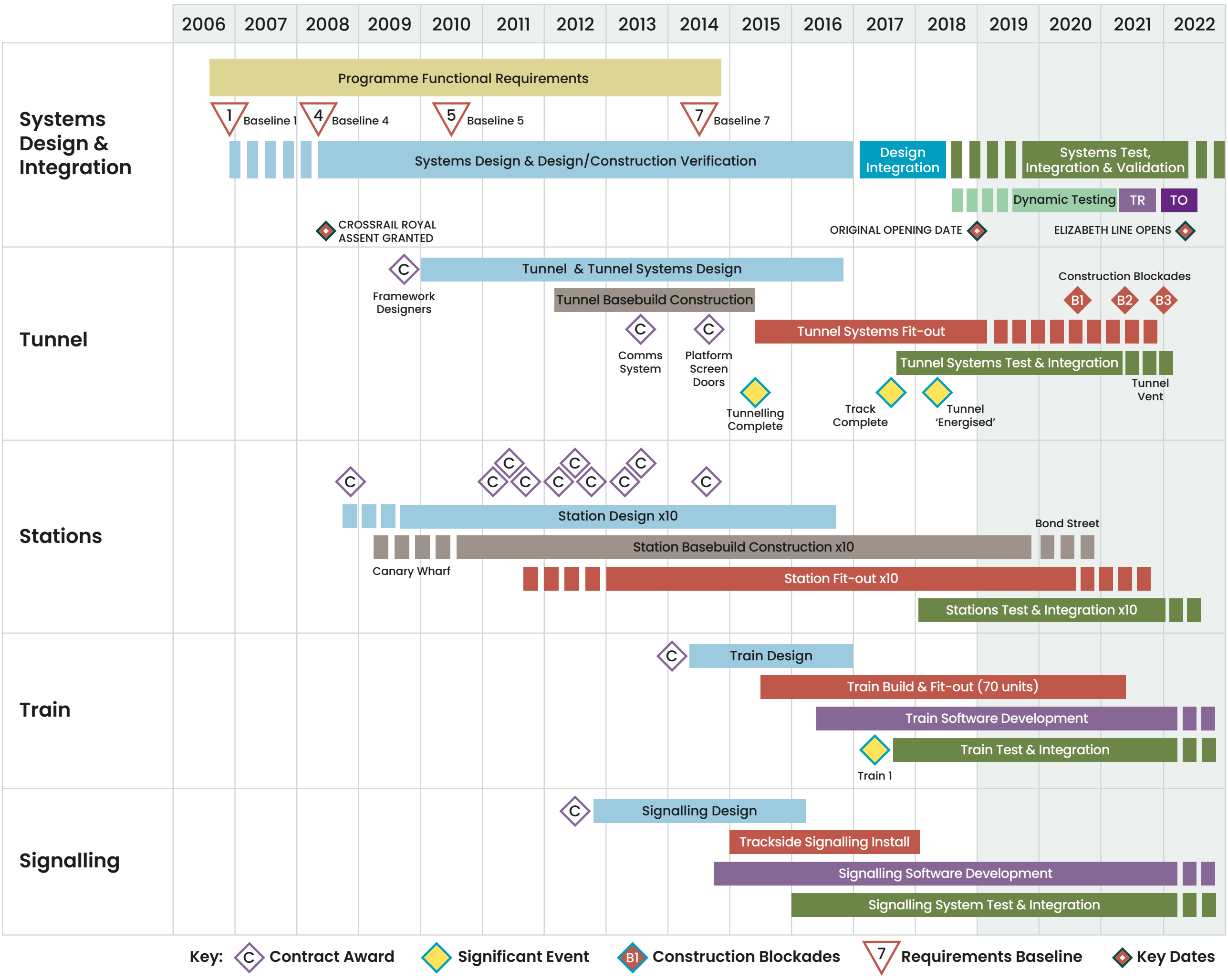


Figure 3 Crossrail timeline 2006–2022

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.

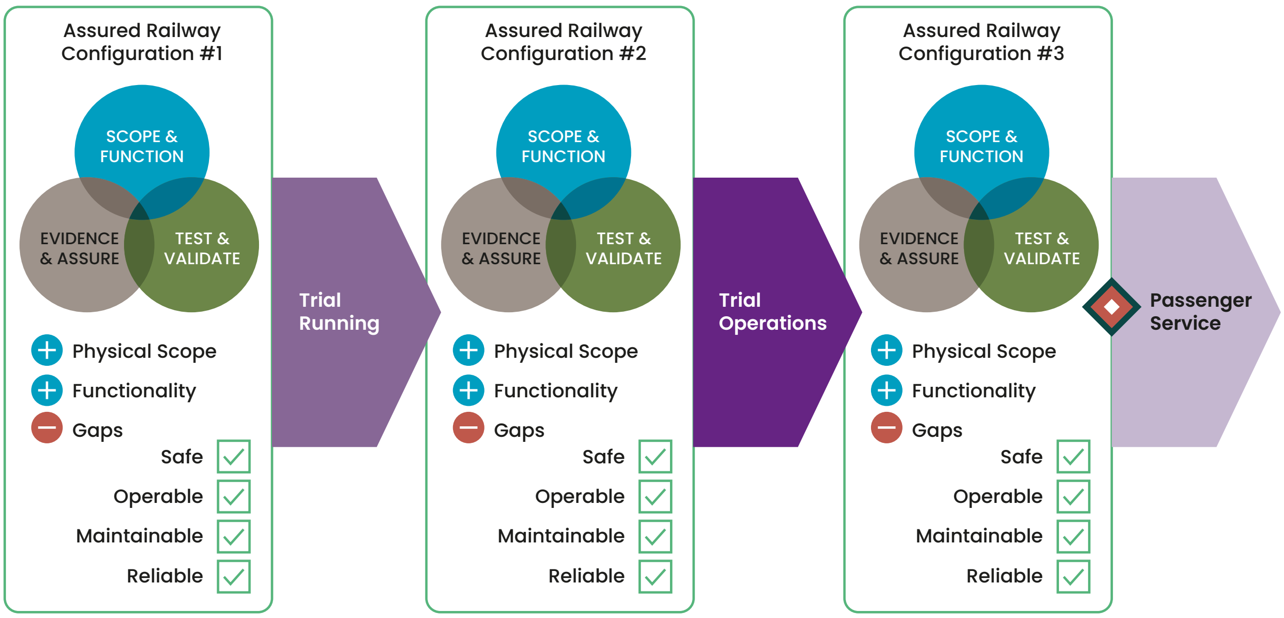


Figure 4 Crossrail layers and phases of integration

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.

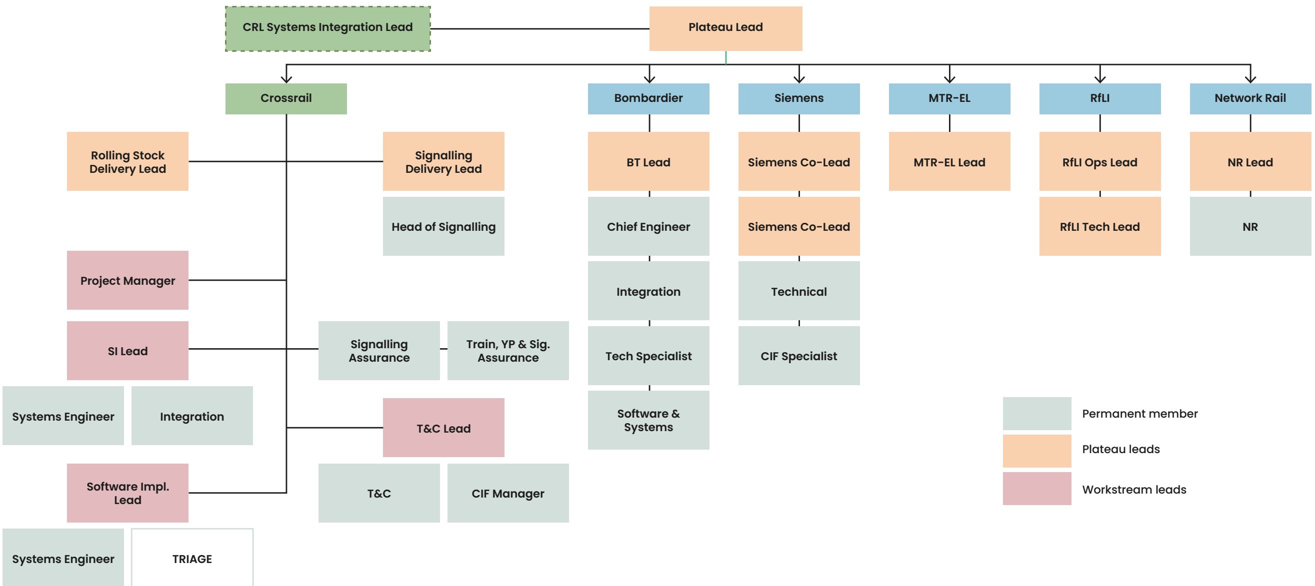


Figure 5 The integration Plateau team

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.

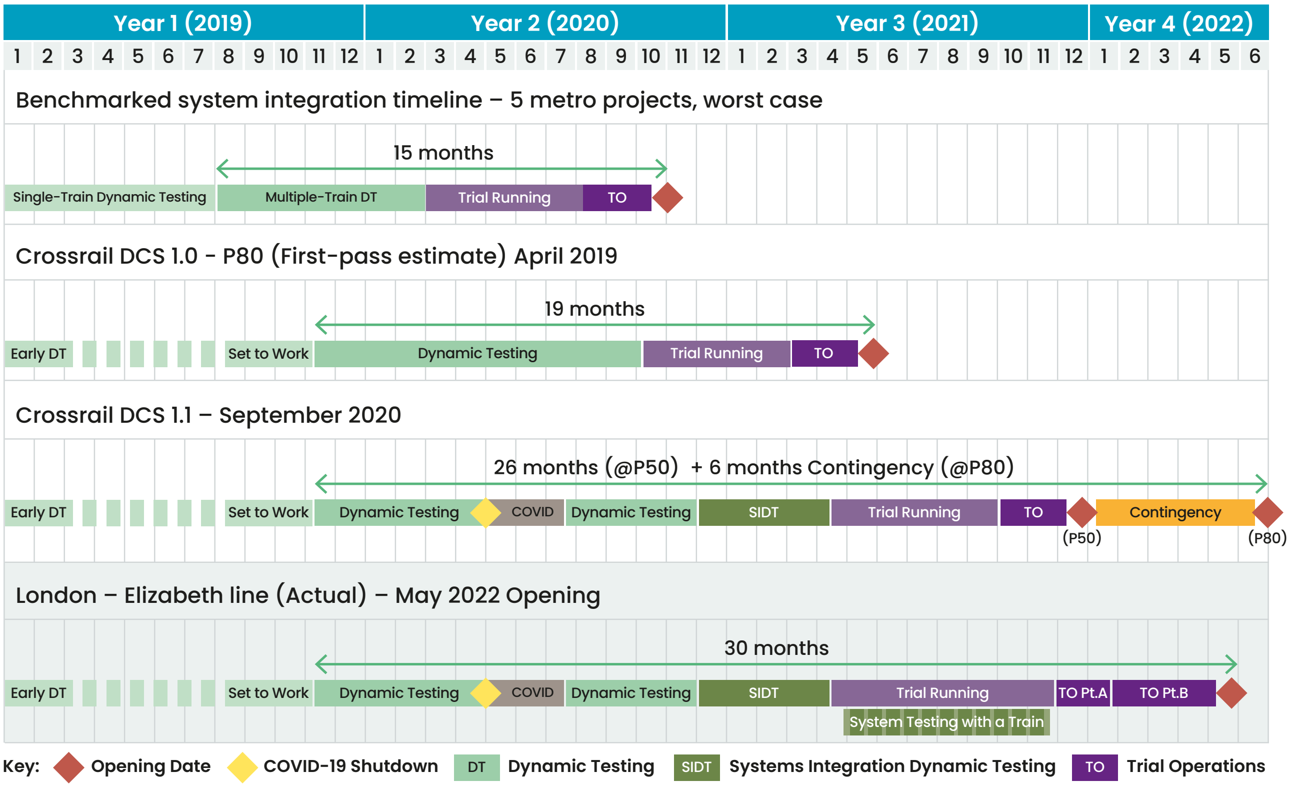


Figure 6 The impact of complexity on software iterations and timescales

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).

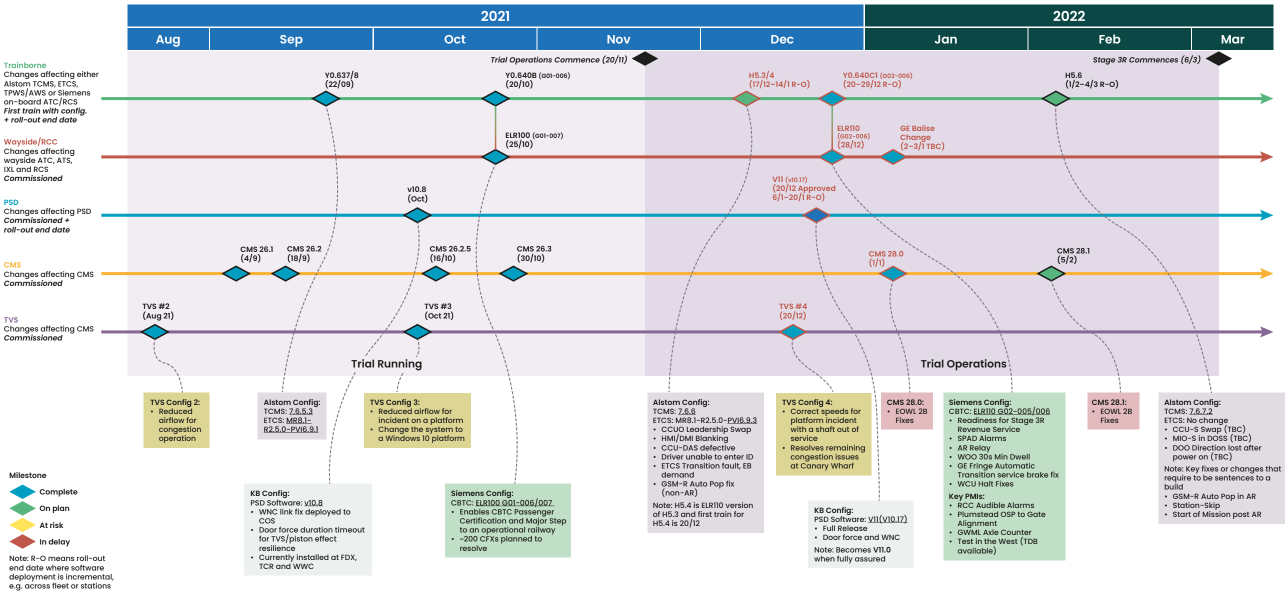


Figure 7 Crossrail integrated software release strategy

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.

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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.

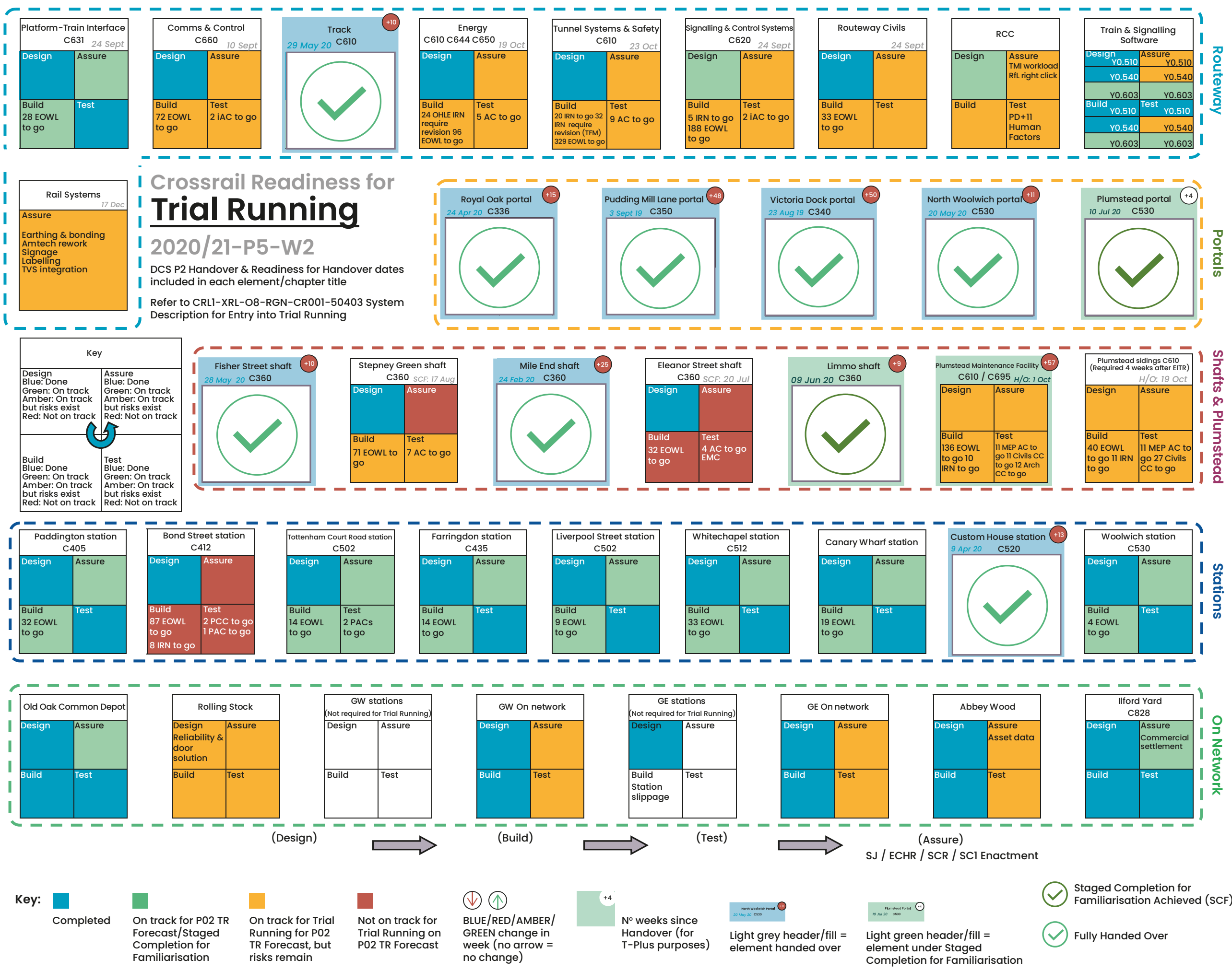

Figure 8 Programme summary 'patchwork quilt' for Trial Running

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.