

Crossrail -Elizabeth Line¹

London, UK



The Zofnass Program at Harvard

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Prof. Spiro N. Pollalis prepared this case study with researcher Dimosthenis Lappas at the Zofnass Program as the basis for research and class discussion rather than to illustrate either effective or ineffective handling of the design, the construction or an administrative situation.

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¹ The case study was based on interviews conducted in London in December of 2018 by Prof. Spiro N. Pollalis with Sir Terry Morgan and Malcolm Taylor of Crossrail Ltd and Mel Ewell as well as on teleconferences with Alan Lamont and David Robertson of Bentley Systems in December of 2018 and Dr. Mike de Silva of Bechtel working for Crossrail until May 2017.

Abstract

Crossrail, the new Elizabeth Line railway project, is currently the largest infrastructure project under construction in Europe. Due to its size, cost, and complexity it can be categorized as a megaproject. The £16 billion (\$21 billion) new railway line will increase the rail capacity of London by 10%, significantly improving the environmental performance of the whole city. Regarding sustainability, this is the “right project.” Nevertheless, in terms of sustainability in a megaproject it is also challenging to “do the project right,” since managers and stakeholders of megaprojects are traditionally reluctant to adopt new approaches. They prefer tried and tested methods in order to avoid risk. Contrary to that perspective, the Crossrail management team pursued innovation and set a precedent in sustainability for a project of this size. Although the project currently (December 2018) faces delays due to the integration of rail signaling systems, Crossrail’s construction process and its innovation and sustainability strategy have established a legacy of good practices and lessons learnt.

Project data

Project name:	<u>Crossrail, Elizabeth Line</u>
Project type:	Railway line
Location:	Greater London, Berkshire, Buckinghamshire, and Essex, England
Area / length:	118 km / 73 miles
Capacity:	10% extra rail capacity for London; 200 to 280 million passenger trips per year
Owner / client :	Transport for London (Old Oak Common to Abbey Wood / Stratford) Network Rail (Liverpool St Main Line to Shenfield & Old Oak Common to Reading) Heathrow Airport Holdings (Heathrow branch)
Project team:	Contractor: 83 construction and logistics contracts
	Engineer/Designer: Various firms
	Facility/Project Manager: Crossrail
	Consultants: Various
Project lifespan	At least 120 years
Current status:	Over 90% complete
Funding model:	Public multi-source funding Government of the UK 60%, Transport for London (TfL) 40%
Delivery method:	Construction Management
Overall investment:	£15.4 billion

1. Introduction

The Crossrail project will deliver the east–west Elizabeth line railway across London. It will have ten new stations, 42 km of tunnels, works to surface railways, and associated depots and maintenance facilities. With an initial £15.8 billion funding, in construction from 2008 to 2019, the new line will significantly increase central London’s rail passenger transport capacity and will have a £42 billion present value net benefit to the UK economy over a 60-year period.²

As a public transport project, Crossrail delivers sustainable outcomes by:

- Relieving overcrowding in existing underground and train services,
- Adding 10% extra rail capacity for London,
- Decreasing trip times across London.

Crossrail brings an additional 1.5 million people within a 45-minute commuting distance of London’s key business districts. 200 million passengers will travel on Crossrail annually. Eight new subsurface stations will be connected by new twin-bore tunnels measuring 21 km in length under London.³ The total length of the line overground and underground is 118 km, connecting business, commerce, and transport hubs. Most notably it will directly connect Heathrow airport with the commercial heart of London in Oxford Street and the business hubs of the City of London and Canary Wharf.

Crossrail Ltd was created as a subsidiary of Transport for London (TfL) to deliver the project to the requirements of sponsors: TfL and the Department for Transport (Wright et al., 2017). It is a publicly funded project, with 60% contributed by the UK Government and 40% by TfL. In October 2007 a funding budget of £15.9 billion was agreed to deliver the Crossrail scheme in its entirety. Following the Comprehensive Spending Review in October 2010, the funding budget was reduced to £14.8 billion.⁴ Part of the funds were raised through a special tax applied only on London’s businesses, the Crossrail Business Rate Supplement. There was also a small contribution from organizations that will directly benefit from the project, such as Heathrow, City of London and the Canary Wharf Group, and a contribution from developers working on regeneration projects in London through a special levy. The project required additional funding in 2018 and is now estimated to cost £15.4, which is still below the original 2007 budget. However, the final cost might further increase by the completion of the project.

Although Crossrail is a publicly funded project, it was managed as a privately owned public company with a Board acting based on best private-sector practices, as the ex-chairman of the company Terry Morgan mentions.⁵

The design and construction of the Elizabeth line represent an example of a highly complex program of projects to be managed, as evidenced by the contractual arrangements required to deliver the systems and infrastructure. Crossrail Ltd has thus far assigned 23 framework design contracts and over 80 construction and logistics contracts.

² “Crossrail Project: Building a Virtual Version of London’s Elizabeth Line.”

³ “Delivering Crossrail, UK: a holistic approach to sustainability.”

⁴ <http://www.crossrail.co.uk/about-us/funding>

⁵ Interview with Prof. Spiro N. Pollalis in London, December 2018. Sir Terry Morgan was the chairman of Crossrail Ltd from June 2009 to December 2018.



Fig. 1. Crossrail route map (source: Crossrail Ltd)

2. Project development – Innovation

Building a complex project of this scale right in the center of a city as busy as London carries risk. Crossrail initially considered the design-build delivery method, transferring the risk to the contractors. Such a proposal was rejected, however, as it could have significantly increased costs due to uncertainties. Instead, Crossrail followed a construction management/traditional method that included detailed design for the main structures of the project and asked for construction bids for specific packages. The company held the contingency costs to manage and mitigate risk and paid particular attention to the procurement process. As Malcolm Taylor of Crossrail Ltd mentions,⁶ “almost all of our contracts were target-cost; we gave the main infrastructure contractors three months so they could optimize the design if they wanted. Some of them radically changed the design – for example from in-situ concrete to precast concrete manufactured off-site - which was good for the project. Our diligence in understanding contractor submissions meant it sometimes took a longer time to award contracts.” He continues, “That type of contract enabled us to agree variations quite quickly with contractors, required to sort out things quickly as the project progressed to everybody’s benefit.”

The company also set up expert committees with external consultants with expertise on specific issues. The expert committees did not make decisions but gave feedback to the project’s engineers on feasibility and optimization. The expert committees were used for procurement, railway systems, and tunneling. The procurement process required a detailed performance evaluation every six months on all major contracts. The detailed assessment, named the “Performance Assurance Framework,” measured performance, drove collaboration, and shared knowledge. The framework covered six key delivery functions:

- Commercial,
- Health and safety,
- Quality (including technical compliance),
- Environment,
- Community relations, and
- Social sustainability.

The Crossrail project “built” two railways: first a digital and then the physical one. The digital

⁶ Interview with Prof. Spiro N. Pollalis in London, December 2018. Malcolm Taylor is the Head of Technical information of Crossrail Ltd.

version was used to explore and facilitate design, construction, and subsequent operation of the actual railway.⁷ As Terry Morgan recalls, “we decided very early at the executive level that Crossrail would be a digital rail, the first digital rail to be implemented in the UK.” This approach is also known as the “digital twin.”

To ensure smooth cooperation and successful digitalization of the new railway, Crossrail Ltd set strict guidelines and standards and required all contractors working on the project to use Crossrail’s processes and software systems. It is common at the beginning of a project for all involved companies to want to use their own processes and software. In such a case, though, the information needs to be compatible, which is expensive and risky. Malcolm Taylor, the Head of Technical Information in Crossrail Ltd, mentions that “the problem with these very large projects is that they are a program of projects, and the trick from an information and data point of view is to be prescriptive and try to make people understand what is to be achieved ... especially when there are multiple designers and contracts requiring coordination. Standards and requirements should be clear, so that everyone understands what’s wanted and the outputs and deliverables are consistent.”

The Crossrail-Bentley Information Academy

To achieve the best possible synergy between the digital and the physical model and to boost innovation, Crossrail created the “Crossrail-Bentley Information Academy” through a technology partnership with Bentley Systems. The Academy was a UK first. As Alan Lamont⁸ of Bentley Systems recalls, “When Crossrail came to us they had a clear vision of what they wanted. They wanted to build this project virtually and physically in parallel, capture digitally all the assets and hand them to the asset owner at the end of the project. The objective given by Andrew Wolstenholme⁹ and Greg Bentley¹⁰ was to improve the delivery of the project making sure that everybody would understand why they were asked to deliver what they were delivering.”

Through the academy, Crossrail pioneers the concept of a common data environment (CDE) and the use of building information modeling (BIM) on a scale that has not been undertaken before, at least in Europe. This has directly enabled the development of innovative engineering design solutions that minimize waste and reduce future costs for maintaining the railway.

The Academy helped to ensure Crossrail was capturing, developing, and sharing best practices on digital information technology with the entire Crossrail supply chain. It provided an enabling force to let all stakeholders understand how Crossrail managed information across multiple linked technology platforms, creating a “Single Source of Truth” within a CDE. A CDE is simply a place in which information comes – or can be brought – together, with a process for storing, sharing, and accessing data in an efficient and secure way. When very large amounts of digital data are being created and shared during a project’s life cycle, the CDE is the ideal environment in which to promote a collaborative working culture across multiple groups, one in which everyone has access to the right information at the right time. Traditionally a CDE has three types of data within it:

⁷ “Crossrail Project: Building a Virtual Version of London’s Elizabeth Line.”

⁸ Teleconference with Prof. Spiro N. Pollalis, December 2019. Alan Lamont is Vice President Global Digital Advancement Academies of Bentley Systems.

⁹ Andrew Wolstenholme was the CEO of Crossrail Ltd from 2011 to 2018.

¹⁰ Greg Bentley is a co-founder and CEO of Bentley Systems.

graphical models, non-graphical data, and documents. What makes it a CDE is the shared use of this single information model across many organizations, engineering disciplines, and contracts.¹¹

Crossrail's contractual structure presented its information management team with a unique problem of having to manage data deriving from different sources. With 23 design contracts, 34 enabling works contracts, and 56 construction and logistic contracts, packaging the information and creating relationships between different types of data was a complex challenge. Recognizing the need for top-down support for digital-information-related initiatives, the Academy presented opportunities for Crossrail to openly share information, enabling the supply chain to innovate and produce world-class information deliverables.

The Academy was set up as a BIM-based linking to live project databases, utilized for design and construction reviews and briefing sessions with various project teams. Because of the virtual nature of the Academy environment, it was ideal for testing innovative ideas. The Academy allowed attendees to investigate the impact of an idea on the existing systems or processes and on the people or environment where it would be used.¹² Unlike other similar initiatives, the Academy was not a product training space but a space to promote processes, standards, and industry examples. Digitalization, both in manufacturing and in processing and the alignment of processes, offer new opportunities and has the ability to reshape the way the industry works. But as Lamont pinpoints, the problem is not the technology but always the people. "They [i.e., the people] would not read anything we write, would not learn something new, so we need to create the environment that has them collaborating at the project level. We were encouraging, enabling, and the interaction was driven by Crossrail but not in a Crossrail office. The Academy is a neutral space that gives all stakeholders the opportunity to think what they want to do, how they are going to do it, and brings everyone on board."

The scale of project information activity for Crossrail can be illustrated by the following:

- Over 5 million documents,
- Over 450,000 drawings,
- 660,000 assets,
- 8,250 users of the information database,
- 450 CAD users.

The digital twin consists of various pieces of information that stakeholders need in order to make decisions at the right time. When a Crossrail model has been built, it can be used to support decision-making and answer questions. In maintenance, for example, data models forecasting when assets might fail are critical. 3D visualizations are effective for maintenance as they provide an immediate spatial understanding of asset location (e.g., high up, in a confined space, close to track). Modeling information is important across the full life cycle of infrastructure (Figure 2).¹³

¹¹ "Crossrail Project: Building a Virtual Version of London's Elizabeth Line."

¹² <https://learninglegacy.crossrail.co.uk/documents/information-academy/>

¹³ "Crossrail: A Case Study in BIM," Ilka May, Malcolm Taylor, Daniel Irwin.

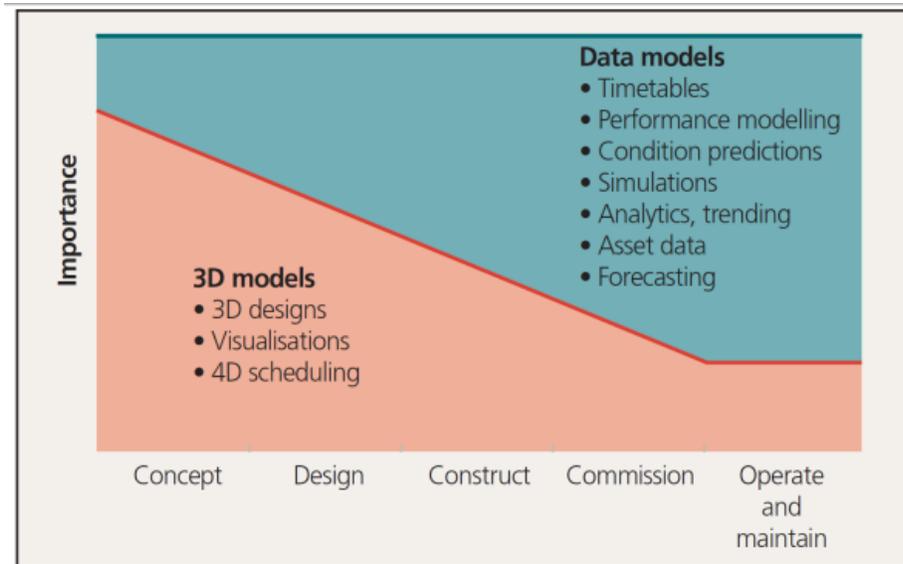


Fig. 2. Modeling information across the life cycle of a project (source: Crossrail Ltd)

Innovate 18

Crossrail has been the first organization within the UK construction industry to develop a strategy and process for managing innovation in a major project environment. Innovate 18 was developed in 2012 by Crossrail in conjunction with Imperial College. The idea came from the then chief executive Andrew Wolstenholme, who convinced all major contractors to contribute an amount for an innovation fund.

Innovate 18 provides a platform to exchange ideas and share knowledge across a diverse community. The network of innovation champions and innovators is drawn from Crossrail, its supply chain, and its partners. The program also connects indirectly with representative bodies, such as the (UK) Institution of Civil Engineers and the (UK) Construction Leadership Council; government bodies, such as Catapult and Innovate UK; and industry bodies, start-ups, and large multinational businesses and organizations from other industries.

Innovate 18 was based on ideas generated from people across the project. It provides a mechanism for exploring market leading technology, exploring new systems, and designing process improvements. Its four themes to guide innovators and help generate ideas are:

- Health and safety,
- Digital-physical integration,
- Delivering efficiencies,
- Sustainable solutions.

At its peak, more than 1,000 people involved in the Crossrail project were accessing the website and were sharing ideas. The database now includes more than 800 innovations, of which more than 400 have been developed. At the heart of Innovate 18 is a commitment to deliver capability, collaboration, and culture. The most important success of the program, as Taylor mentions, was the commitment and enthusiasm showed by people who came up with ideas; “they were eager to make them happen.”

The Crossrail innovation process follows five simple stages, as shown in the following figure. Two achievement examples of the Innovate 18 program are presented in the Appendix. The concept of Innovate 18 has now developed into a UK-wide initiative called “i3P” (Infrastructure Innovation Industry Platform).

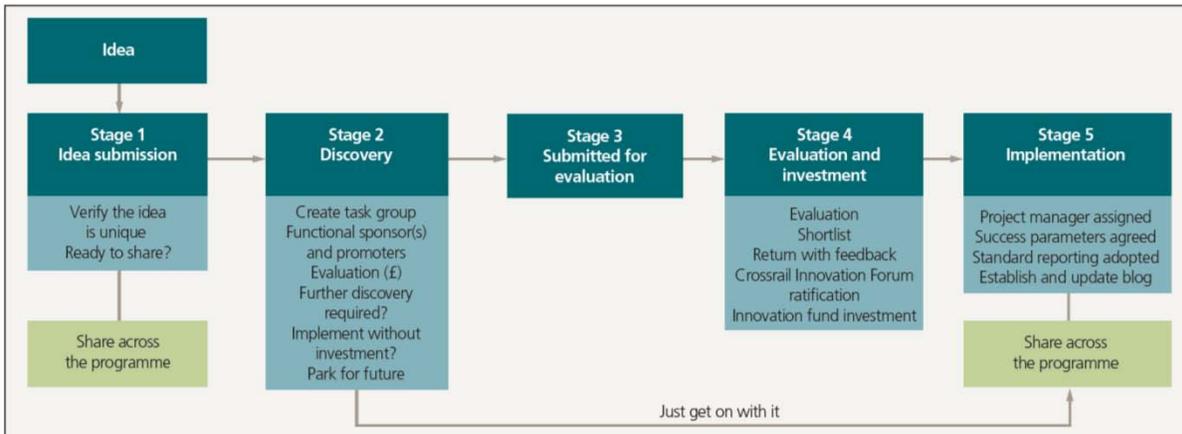


Fig.3. The five stages of the innovation process¹⁴

Learning Legacy

In February 2016, Crossrail launched a new online resource to share insight from the project for the benefit of the industry: the “Crossrail Learning Legacy.” There are nearly 500 documents available so far, and new content will continue to be published every six months.

Since its launch, the project has published 94 environmental learning legacy documents. These include case studies, micro reports, good practice documents, and further supporting documents such as toolkits, plans, procedures, and policies.¹⁵

The website has been well received, with 8,758 visitors over the first year. Crossrail’s environment team attended 18 dissemination events and six webinars were completed, jointly hosted by the Institute of Environmental and Assessment (IEMA) and the Construction Industry Research and Information Association (CIRIA).

3. Main sustainability features of the project

Crossrail is one of the first projects of this scale to consider sustainability from the beginning and embed sustainable thinking into its decision-making. An important first step was to produce a sustainability strategy. This strategy was published in 2009 as construction of the Elizabeth Line began at the Canary Wharf site. The strategy set a holistic approach aimed at delivering improvements in economic, environmental, and social sustainability. It established seven sustainability themes that were aligned to goals of its two sponsors, TfL and the Department for Transport, with a few additions that were pertinent to the type of project but not covered in the goals of the sponsors, as for example the sustainability impact of materials. Key sustainability initiatives and objectives and targets were set, when possible. Where there were no available

¹⁴ DeBarro et al, “Mantra to Method: Lessons from Managing Innovation on Crossrail, UK.”

¹⁵ Crossrail Environmental Report 2017.

relevant benchmarks, the approach was either to use informed judgment to select a nominal target, or to set an objective with a view to observing what could be achieved and providing benchmark data for subsequent projects to use.

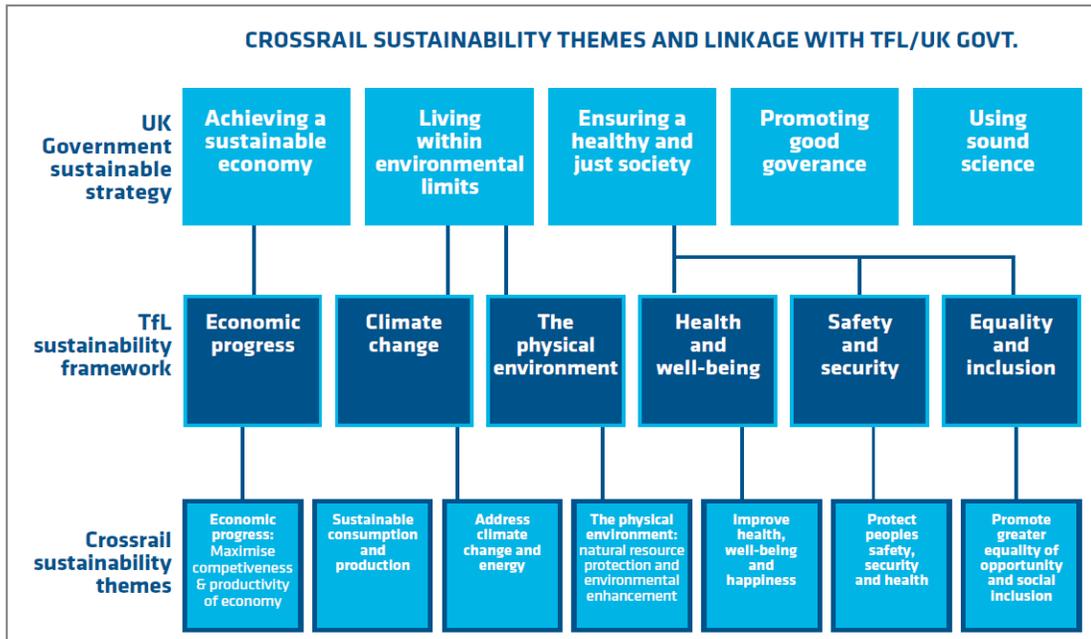


Fig. 4. Source: Crossrail, Sustainability Summary Report 2018

In terms of economic sustainability the project is estimated to generate at least £42 billion net present value for the UK economy over 60 years. It will boost London's competitiveness by easing congestion, by shortening trip times, and by increasing accessibility.

Crossrail is also the first major transport project in the UK to design the stations, surrounding areas, and oversite development opportunities at the same time. Besides high-quality public space, three million square feet of office, retail, and residential space is also being delivered directly above or near the new central stations. This approach and wider master-planning maximizes regeneration along the route of the project. Independent forecasts show that the project will unlock or accelerate the supply of over 90,000 homes and over 4.4 million square meters of commercial office and retail space, adding £10.6 billion to property values in London.¹⁶ During construction, Crossrail has supported over 55,000 jobs in the UK, and it has actively engaged with local suppliers to maximize the economic benefits to UK businesses by trying to attract a wide and diverse base of potential bidders for Crossrail work and ensure UK businesses, irrespective of size, have been aware of the available opportunities.

Crossrail set tight environmental targets during construction. 99.7% of the 8 million tons of excavated material was beneficially reused to develop new nature reserves, wetlands, recreational facilities, agricultural and industrial land. Most notable among these is the creation of the Wallase Island natural reserve in Essex in collaboration with the Royal Society for the Protection of Birds (RSPB). The natural reserve has already become one of the most important sites for migrating birds in Europe. 80% of this material was transported by rail and water, significantly reducing trucking in the streets of London. Demolition and construction activities generated 539,499 tons of

¹⁶ Crossrail, Sustainability Summary Report 2018

waste material. 99.6% of the waste was diverted from landfill with 39% reused or recycled, exceeding the target of 20%. The project also minimized impact on air quality by having 83% of construction equipment fitted with emissions controls, exceeding the target of 80%.

Crossrail and Network Rail have used the biodiversity accounting methodology of The Department for Environment, Food and Rural Affairs (DEFRA) to determine the value (expressed as biodiversity units) of habitats lost, enhanced, and created as a result of the project. The construction of 42 km of tunnels and 10 new stations in the central section results in a net loss of biodiversity units. Where possible, the project found ways to turn some of this loss to gain through initiatives including green roofs and landscaping. A target was set to achieve 80% of the possible biodiversity units it identified, and the project is currently achieving 91%. On the surface section of the rail, Network Rail set a target of no net loss of biodiversity units. At 59% surface rail completion, the project is on course to provide biodiversity enhancements to sites currently managed by local wildlife trusts, and it is projected to do the same in the remaining 41% of surface rail.

The project has been committed to reducing its carbon footprint by reducing the energy consumption of the operational railway, the embodied energy in construction products, and the energy used during construction. Crossrail has achieved a construction-related carbon emissions reduction of 18.6%, against its target of 8%. Crossrail Ltd developed a tool that allowed contractors to forecast what the carbon emissions would be for their equipment. The tool allowed contractors to decide the type of equipment they should use to reach their contract's carbon targets. Reductions in the embodied carbon footprint have been made possible through the use of concrete with cement substitutes. Crossrail's concrete specification required a minimum of 50% cement substitutes, but the project has been able to increase this amount in some sites to as much as 72%. Crossrail set targets for weight and energy efficiency for the train cars. These targets were 350 tons unladen weight per 10-car train and 24 kilowatt-hours/train, respectively. The last figure equated to 55 g CO₂ per passenger-km. The weight target has been exceeded, with a little under 319 tons unladen weight. This lighter train has assisted in meeting the energy efficiency target. Tests on the efficiency of the trains are still being carried out, but the latest information indicates an efficiency in the order of 14 kWh/train. This equates to approximately 32 g CO₂ per passenger-km, making the new trains among the best in their class for energy efficiency.¹⁷

To further reduce energy consumption, LED lighting has been installed in the tunnels and stations, which requires 62% of the energy used in standard light fixtures. Sophisticated lighting controls include electricity submeters integrated into the building management systems, allowing optimization of energy performance. In addition, energy-efficient elevators and escalators have been specified for the stations. The decision to move from conventional to LED lighting has significant life cycle cost and carbon savings benefits. Benefits of LED lighting include a brighter illumination, reduced maintenance requirements, and 23,400 tons CO₂ reduction. The cost of LED lighting and fittings was £1.7m, while the savings are estimated at £19.9m: £2.4m energy saving, £17.2m reduced labor saving, £0.2m material saving, and £0.1m CO₂ commitment.

Sustainability has been a key driver on most components of Crossrail. An innovative renewable energy system will supply over 30% of the energy needed on the Old Oak Common depot, the

¹⁷ Crossrail, Sustainability Summary Report 2018.

main maintenance facility of the project. The hybrid renewable energy system integrates ground source heating and cooling to control the temperature of the main depot building from a combination of energy piles and 150 m deep bore holes, with three different types of thermal technologies creating an innovative system. It is the first rail depot in the UK to introduce these environmentally friendly measures to this extent, by fully integrating separate systems, which will help to reduce its running costs and reduce CO₂ emissions by 35%.

Crossrail adopted the Civil Engineering Environmental Quality (CEEQUAL) and Building Research Establishment Environmental Assessment Methodology (BREEAM) schemes to ensure and evaluate sustainability performance for every component of the project.

Environmental assessment ratings – CEEQUAL¹⁸

All civil structures, such as tunnels, portals, shafts, and the surface sections, were assessed using CEEQUAL and have either achieved rating or are on target to do so. The Thames tunnel and western tunnels contracts that were completed in 2016 performed particularly well in the categories of water resource management and of management of relations with local community and stakeholders, respectively.

CEEQUAL	Target rating	Client and interim design rating	Construction rating
Western tunnels	Excellent	Excellent	Excellent achieved
Eastern tunnels	Excellent	Excellent	Excellent achieved
Thames tunnel	Excellent	Excellent	Excellent achieved
Sprayed concrete lining structures	Excellent	Excellent	Excellent achieved
Paddington Integrated Project	Excellent	Excellent	Excellent achieved
Eleanor Street / Mile End shafts and head houses	Excellent	Excellent	Excellent achieved
Victoria Dock portal	Excellent	Excellent	Excellent achieved
Pudding Mill Lane	Excellent	Excellent	Excellent achieved
Royal Oak portal	Excellent	Excellent	Excellent achieved
Connaught tunnel	Excellent	Excellent	Excellent achieved
Stockley flyover	Excellent	Excellent	Excellent achieved
Acton dive under	Excellent	Excellent	Excellent achieved
Western outer track infrastructure	Excellent	On target	Excellent achieved
Western outer track electrification	Excellent	On target	Excellent achieved
Old Oak Common Paddington approaches	Excellent	On target	On target
West stations	Excellent	On target	On target
Northeast section	Excellent	Excellent	On target
Southeast section	Excellent	Excellent	Excellent achieved

Fig. 5. CEEQUAL performance (source: Crossrail, Sustainability Summary Report 2018)

Environmental assessment ratings – BREEAM¹⁹

All new stations, depots, and maintenance facilities are on target to achieve a final BREEAM rating of “Very Good.” This was the first time that BREEAM was used for the evaluation of underground

¹⁸ Crossrail, Sustainability Summary Report 2018.

¹⁹ Crossrail Environmental Report 2017.

stations, and the “Very Good” target seemed a sensible and safe option. BREEAM Bespoke, a variation of BREEAM with specific criteria for underground stations, was used after the Crossrail sustainability team cooperated with the British Research Establishment (BRE), the publisher of the rating system. Crossrail continues to work with contractors to identify where overall performance can be improved, subject to engineering feasibility, cost, and program constraints. Several opportunities are being investigated that will consolidate the “Very Good” rating and contribute to an overall performance score toward the higher end of the rating band. The majority of assets being certified under BREEAM are likely to be fully certified for their post-construction rating during 2019. According to Crossrail’s former Sustainability Manager Dr. Mike de Silva,²⁰ as of January 2019, three out of six completed stations managed to surpass the “Very Good” target and achieved “Excellent” rating.

BREEAM	Target rating	Design stage rating	Post-construction rating
Tunnelling and Underground Construction Academy	Very Good	Achieved	Excellent achieved
Paddington station	Very Good	Achieved	On target
Bond Street station	Very Good	Achieved	On target
Tottenham Court Road station	Very Good	Achieved	On target
Farringdon station	Very Good	Achieved	On target
Liverpool Street station	Very Good	Achieved	On target
Whitechapel station	Very Good	Achieved	On target
Custom House station	Very Good	Achieved	On target
Abbey Wood station	Very Good	On target	On target
Woolwich station	Very Good	On target	On target
Ilford logistics and stores	Very Good	Achieved	Achieved
Ilford operations and welfare	Very Good	On target	On target
Plumstead depot	Very Good	On target	On target
Old Oak Common depot	Very Good	On target	On target

Fig.6. BREEAM performance (source: Crossrail Environmental Report 2017)

Besides the design and post-construction stage rating, Crossrail Ltd came out with a simple but very innovative technique that will ensure the sustainable performance of the project in the long term. BREEAM information has been tagged to the relative parts of the digital twin, which will be handed to the operator. Every time the operator alters or replaces a component of the project, they will get a notification regarding the way it might affect credits and the overall BREEAM performance, prompting informed choices. As de Silva mentions, “the major sustainability benefits from the digital twin are yet to come ... nobody seems to have made that connection before, and we are hoping that will qualify for a BREEAM innovation credit.”

4. Economic performance

Crossrail changes the rail capacity of London, and economic benefits should be examined on a citywide scale. London’s economy and competitiveness will benefit from the jobs created during construction and operation and the time saved from improved transport connections and accessibility to millions of people. According to Terry Morgan, the estimate of £42 billion over a period of 60 years made by the Treasury is quite conservative. So, in 2012, Crossrail Ltd

²⁰ Teleconference with Prof. Spiro N. Pollalis, January 2019. Dr Mike de Silva, an employee of Bechtel, served as the Sustainability Manager of Crossrail Ltd until May 2017.

commissioned an independent study to assess the economic impact of the project by 2020. The results showed that the country's GDP will benefit by £5.5 billion. That outcome enabled developers to have confidence in the project and boosted the regeneration projects across the line. When they commissioned the same research in 2017 the result increased to £11 billion GDP benefit, again by 2020.

In addition, the city of London will benefit from the regeneration schemes, since key stakeholders such as TfL and the local authorities have contributed funding alongside Crossrail to develop designs and deliver public space improvements around the stations. Three million square feet of high-quality office, retail, and residential space is also being delivered directly above or near the new central stations. Twelve property developments are estimated to raise £500 million toward Crossrail's funding package – reducing costs to the taxpayers. Moreover, and as already mentioned, independent forecasts show the project is unlocking or accelerating the supply of over 90,000 homes and over 4.4 million square meters of commercial office and retail space, adding £10.6 billion to property values in London.²¹

Besides the citywide economic benefits, the focus on innovation and on embedding sustainability from the early stages differentiates Crossrail from other megaprojects. Although there are strong indications that the innovative and sustainable features have brought down construction and operational costs, monetizing these benefits in detail proves difficult. Further research and access to data are needed that exceed the scope of this case study.

Digital twin – Crossrail-Bentley Information Academy

Information technology and management costs for hardware, software, licensing, and staff for the duration of the design and construction stages of the project are approximately £250 million, or about 3% of the cost of the central section of the contract works delivered directly by Crossrail.²² The cost of maintaining and operating Crossrail during its life cycle is expected to be two to five times the capital cost of construction.²³ According to Taylor, the information technology and management systems, including the Common Data Environment, saved the project almost £120 million.

Innovate 18

The total cost of the Innovate 18 program was about £3 million and it is estimated that the benefits already amount to three times that figure, which will probably double by the end of the construction period.²⁴ The monetary benefits of Innovate 18 might seem limited compared to the total budget of the project. This is in part due to the late initiation of the program, with many of the innovations reaching maturity late. However, the Crossrail innovation program was set up without intended financial benefits as a key performance indicator; rather its objectives focused on number of innovations submitted to the platform and rates of diffusion of those innovations across sites. There are a number of intangible benefits, such as health and safety improvements, and additional

²¹ Crossrail, Sustainability Summary Report 2018.

²² "Crossrail Project: Building a Virtual Version of London's Elizabeth Line."

²³ "Crossrail Project: Building a Virtual Version of London's Elizabeth Line."

²⁴ Andrew Wolstenholme, "Breaking the Mold: How Crossrail's Innovate 18 Program Works."

behavioral benefits associated with an innovative culture, such as increased collaboration and team-building. Although hard to quantify, they are arguably as important as financial benefits. The Crossrail innovation program has shown that there is a direct correlation between performance and innovation.²⁵

5. Delays resulting from the integration of signaling

In August 2018, it was announced that the opening of the core Elizabeth Line would be delayed from December 2018 until Fall 2019. In December 2018, that date was also put in doubt, with Crossrail Ltd indicating that a new opening date will be announced after further reviewing the progress of the project. The delay is principally due to severe signaling integration problems. Crossrail line passes through four different rail signaling systems, and integrating Crossrail's high tech trains with those systems proved a complex problem that had been underestimated.

According to Taylor, during the first few years of the project there was a reassurance that the regional train authority, Network Rail, would install a new standard signaling system across London and southeast England, the ERTMS (European Rail Traffic Management System). A few years ago, Crossrail Ltd realized that this would not happen. According to Terry Morgan, the problem lies in a shortage of expertise on systems integration combined with a responsibility gap between Crossrail Ltd, responsible for the construction management of the project, and TfL, responsible for the acquisition of the trains. The funding model for the trains TfL finally chose²⁶ delayed the delivery of the trains by 18 months, reducing the available time for full-scale system integration tests. Therefore, despite Crossrail Ltd completing the main construction program within schedule and at 12% less than the original budget, the signaling integration problems delayed the project. Although the delay is shorter than for similar projects of that scale, there is pressure because of lost revenues for the city of London. TfL's annual ticket revenues for the new line were forecast to exceed £800 million per year starting in 2019/20 and over £900 million per year after 2022/23.²⁷

6. Conclusion and lessons learned

Crossrail, the new Elizabeth Line, brings significant environmental and economic benefits to the city of London and the UK. On a citywide scale, the assessment of benefits and costs indicates a strong business case for the project, in particular in its ability to reduce congestion on London's existing transport network and allow London to generate jobs. The cost for constructing the new railway is £16 billion, while the benefits to the wider UK economy are estimated to be at least £42 billion. Besides being the "right project," Crossrail has also been "done right." Megaprojects usually follow well-established practices and avoid innovative or sustainable approaches, considering them to be risky and costly. However, Crossrail emphasized innovation and embedded sustainability from the beginning, setting a precedent for projects of that scale. The sustainable performance is confirmed for all components of the project with the use of the BREEAM and CEEQUAL rating systems. As already mentioned, there are strong indications that the innovative and sustainable

²⁵ Antoine Vernet, "Crossrail Innovation Programme – Innovation Evaluation Report."

²⁶ The initial decision was to use a PFI (private funding initiative) to fund the trains. TfL found this solution expensive and persuaded the government to increase the organization's borrowing capacity in order to directly buy the trains.

²⁷ "Transport for London Business Plan 2018/19 to 2022/23."

features have reduced construction and operational costs, though monetizing this in detail proves difficult, partly due to the large scale of the project. The Innovate 18 program presents an example of how innovation can be achieved on large projects and showcases that such a program should be implemented from a very early stage for substantial benefits. The “digital twin” strategy and the adoption of innovative solutions through the creation of the Crossrail-Bentley Academy provided innovative engineering design, minimizing waste and reducing operating costs. The Academy proposes a new way for delivering projects, bringing together design/construction with operations as well as with technology firms. It sets a precedent for integration between physical and digital models and an alignment of standards and procedures, creating a legacy for a practice that will probably become the norm for future infrastructure projects. Bentley is already multiplying the concept by opening a network of academies across the world to support projects and provide lessons learnt from previous projects, including the signaling problems Crossrail is currently facing.

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Abbreviations

BIM: building information modeling

BRE: Building Research Establishment

BREEAM: Building Research Establishment Environmental Assessment Methodology

CDE: common data environment

CEEQUAL: Civil Engineering Environmental Quality

ERTMS: European Rail Traffic Management System

RSPB: Royal Society for the Protection of Birds

TfL: Transport for London

Appendix

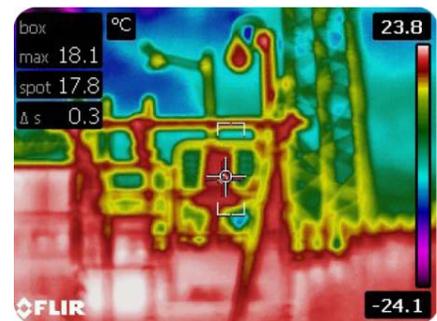
Innovate 18 - Two Achievement Examples

Thermal imaging for monitoring concrete

Innovation theme: Health and Safety

Scope: Investigate the use of thermal heat camera technology to understand the curing characteristics of sprayed concrete lining works so that advancement rates can be reviewed and risk of falling concrete from under-strength concrete mitigated through early identification.

Progress: Cameras were procured at BFKJV (C410) and trials conducted on behalf of Crossrail's Chief Engineers Group. Trials demonstrated that the cameras could be effective in monitoring concrete behavior while curing. An initial report was published. Further trials will be conducted with a more compact product that attaches to mobile phones.



Use of drones on a construction project

Innovation theme: Digital-physical integration

Scope: Procure drones to develop a protocol for construction use and to understand the potential future benefits of this technology in a construction environment.

Progress: Two drones have been procured and a team of staff from different project disciplines, including a site supervisor and a health and safety representative, have been trained to safely operate them. The team has produced a working procedure for flight use, reflecting industry regulations and good practice guidelines.

