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Digital Construction Strategies and BIM in Railway Tunnelling Engineering

Georgios Kapogiannis and Attwell Mlilo

Abstract

Technology has been a strong driver for industrial efficiency in the twenty-first century. Rapid growth in infrastructure projects such as tunnels is synonymous with both disruptive and supportive technologies that automate operations. The sector has rapidly risen to the challenge from buyers demanding a more digitalised experience when looking to (re)design new tunnels. Currently there are projects in the United Kingdom, Greece and Italy investing in tunnels for their transport networks to help commuters to travel quicker. We could argue that construction has evolved because the tunnels developed nowadays are expected to last for several generations but such an argument is count intuitive. Think of having to spend billions of pounds for a tunnel that does not provide an enhanced travel experience and in a few years' time requiring a major investment to remodel in order to operate it. This chapter discusses what, why and how digital construction can add value during the lifecycle of a tunnel.

Keywords: digital construction, building information modelling (BIM), tunnel modelling and management, asset management

1. Introduction

Technology has been a strong driver for industrial efficiency in the twenty-first century. Rapid growth in infrastructure projects such as tunnels is synonymous with both disruptive and supportive technologies to automate operations. The tunnelling sector has rapidly risen to the challenge from tunnel asset owners demanding more digital design solutions when procuring new tunnels. Currently there are projects in the United Kingdom, Greece and Italy investing in tunnels to improve transport capacity and help commuters to travel quicker. We could argue that construction has evolved because the asset developed in now expected to last for several generations but such argument is intuitive. Imagine having to spend billions of pounds for a tunnel that does not provide an enhanced travel experience and in a few years' time requiring a major investment to remodel in order to operate it. Construction cannot afford to remain stuck in past and must transform to improve delivery efficiency and sustainability.

The World Economic Forum (2016) has developed a transformation framework for the construction industry listing 30 measures of best practice. It highlights three important areas of transformation from its traditional approach. Firstly, it has to be

open for innovation so that opportunities from new technologies, materials and tools are exploited to reduce production costs. Secondly, it should consider adopting mechanised and automated production systems alongside offsite construction techniques to speed up the construction process and enhance timely completion of projects in a collaborative environment. However for projects of high complexity such as tunnelling that involves a number of strategic and operational decisions from the client, designers, contractors, the supply side and regulators, BIM can provide a collaborative platform. Through vertical and horizontal collaboration, processes and resources will be optimised to deliver the client's requirements. Inadvertently this generates a significant amount of data, which needs to be integrated and communicated to the stakeholders so that optimum solutions are agreed on and value is created. Digital construction is an adoption of technology driven initiatives that aim to make use of advances in Information and Communication Technologies (ICT) to enhance integration.

The integration model highlights the need to bring together people, processes, and products of the construction project to deliver value to the client in a more efficient and sustainable way. The third area pivots on the role of project management and the control of costs in the design and planning stages. When procuring projects, contracts are designed to achieve optimum risk sharing across the supply chain with agreed monitoring mechanisms. Lately, the momentum within construction has shifted from the focus on the top down approach of project delivery to more collaborative approach that seeks to satisfy clients' requirements. Results of embracing digital approaches to construction are increasingly yielding positive results and more projects that would otherwise pose high risk of cost overrun are being delivered timely and on budget. Digitalisation of procurement process through the use of approaches such as e-procurement, e-tender and e-sourcing has increased cooperation between client and contractors because of the confidence developed through sharing of accurate data and clarity of information. This has enabled misunderstanding and barriers of culture to be better managed.

In the 1970s, nearly all stakeholders in the construction sector felt challenges of the fast growing technologies and they started to consider improvements to project processes. In the early 1980s the UK government introduced compulsory competitive tender to harness opportunities of growing competition to reduce overall construction cost. This was later relaxed in the early 1990s because of the insecurity it created, and resulted in greater fragmentation in the delivery of projects. Latham's report in 1994 on constructing the team emphasised the need for working collaboratively by collaborating with the supply chain to reduce construction costs and deliver projects more predictably. Construction projects continued to face twin challenges in the wake of the new millennium. They must deliver client value while also have to be resilient to the normality of changing climate and users behaviours. Lean management approaches emerged in the early 2000s and were considered for wider application in Virtual Construction which then became what we know as building information modelling (BIM). BIM provides a digital representation of physical and functional characteristics of a facility which can easily be communicated with non-technical stakeholders. The sharing of knowledge gives clarity and shared vision of the project and the resource required in a more reliable manner so that appropriate decisions on its life-cycle can be made.

BIM is a relatively new paradigm [1] in the construction industry trying to integrate three pillars: people, process and technology to deliver assets that meet client's requirements. BIM extends management information system (MIS) and sometimes it is referred to as a specialist business information management system for construction projects. Through BIM key requirements are captured, analysed and shared to achieve higher levels of collaboration. It is in fact an effective tool for

stakeholder engagement as it enables them to take advantage of technology that is linked to a common data environment (CDE), which can be remotely accessed at any time. The added value is that it integrates collaborative technologies and fosters the development of a collaborative culture through the project life cycle. An integrated collaborative environment brings to light projects challenges so that they are managed in a proactive fashion. Since 2016, BIM was made mandatory in the UK for centrally funded projects with the aim of realising a 33% cost reduction and to develop faster delivery schedules that could reduce overall project duration and emission by 50% (Construction 2025 Report).

The use of BIM collaborative approach in the UK railway industry is so far limited to the construction of new lines like Cross Rail and High Speed link 2 (HS2). Its use in a complex operational environment like that of track renewals and monitoring of tunnels and other structures will need adaptation. Vast amount of existing data from various work streams and in various formats need integrating into management intelligence to develop accurate, prioritised maintenance plans to optimise asset availability, essential for efficient running of train services [2].

In the UK, partnerships and collaborative working have long been the preferred method of procuring railway maintenance projects [3] to maximise efficiencies. The UK government construction strategy and its commitment to long-term partnerships to deliver infrastructure projects is revolutionising ways of working and data management techniques. Rapid advances in technology, increases in capacity to handle large volumes of data at lower costs and the development of quicker data analysis tools are increasingly making data management at the core of strategic planning for organisations [1]. Improving asset data management will provide more accurate baseline data and facilitate multi-use of existing data to reduce unnecessary reworks. However, the future use of partnerships to procure railway maintenance work will need adaption to the new ways of working.

Railway asset maintenance disciplines can standardise their approaches and adapt these modern approaches to suite their unique requirements. Furthermore, in April 2016, the UK government mandated, centrally funded projects procuring public assets to be delivered in fully collaborative 3D, BIM environment [4]. UK rail operators invest millions of pounds in upgrading rolling stock but the state-of-the-art trains often run on much older network infrastructure that consists of tunnel sections the majority of which were constructed over 150 years ago. The railway tunnels were built to last but eventually there comes a time when elements need upgrading and/or replacing after degradation resulting from various factors including vibration, high-speed air flow, corrosion, water ingress and vegetation growth. Poor construction techniques in the past and changing ground conditions also occasionally cause weak points that trigger the need for maintenance works [5]. To ensure safe operation of railway tunnels, they have to be continuously monitored with a tunnel management strategy in place to determine when it is time to take corrective action to mitigate any potential risks. Maintaining existing assets is as important as delivering capacity improvements through the construction of new lines and services for UK railway operators. However, tunnel repair works often cause service disruptions and are a challenge to deliver safely due to space and logistical constraints. As more tunnels are built to meet the rising demand in railway usage, the need for tunnel maintenance will also increase.

2. Integration and collaboration

The multitude of internal stakeholders involved in the briefing, designing, construction and commissioning of a project means that there will be varied interests.

In traditional project delivery methods, fragmentation has been the case that often starves off collaboration to create communication gaps. When the client and the construction team share a common goal on the project, conflicts are reduced and focus is on the project. This enhances cooperation, better stakeholder management and improves chances of successful delivery outcome.

Stakeholders can be an asset to the project when a collaborative environment is developed to enable project data and information to be held in a common data environment (CDE) accessible to the team to support decision-making. Design drawings produced in the formats usable by all, including specialist subcontractors, will reduce requests for customised information from the designers. A collaborative team must maintain an unlimited access to data and information to enhance their knowledge in dealing with problems and thus supporting both decision-making and problem solving. Rowley and Jennifer refer the continuum from data to information and information to knowledge as the principles of the hierarchy of human understanding. This reinforces the importance of data and information management to improve delivery performance of projects.

Front loading time to design and plan for the project in the project definition phase will pay off in the long run, the project team is able to anticipate risk and set mitigation plans and contingency. Design and sequencing issues can cost up to 10 times more to rectify if identified during the construction and later phase of the project life. Technology such as virtual reality (VR) is now available to enhance solutions and should be prioritised for risk assessment.

Figure 1 reinforces the importance of technology as an integrator of people, processes and organisations in the integrated construction environment. This must however, be supported by setting clear communication channels and responsibilities of project team members.

The sharing of data and information, whether formal or informal, can be enhanced by Information Communication Technologies (ICT Technology enables visualisation of production systems and subsystems, so that clashes are detected early in the design and planning stages and resolved. With improved project planning, logistics, both local and across borders, will be coordinated with greater efficiency. Supply chain management also improves which helps in developing trust and a shared culture of quality shared across the supply chain.

Collaboration in Lean and Agile project management show that could work interactively, integrated and intelligent in a unique way to support decision making, problem solving and also pre-identifying project risks. The core requirement is to seek accurate data, the right information that is shared among trustful resources and could add value to the final product (asset).

Although collaboration aims to support information sharing, increased interactions also helps project teams to perform more effectively and efficiently. This further moderates the effects of collaboration on team member learning. Beyond

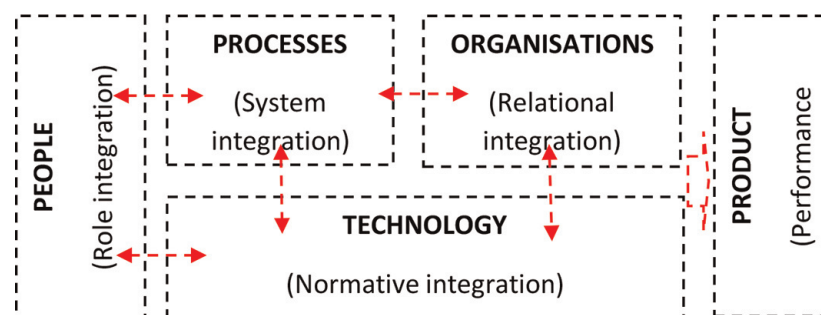


Figure 1.
Integrated construction environment.

the productivity issues, decision making in a collaborative working environment are made more is occurred effectively and thus problems could be solved promptly.

Since the late 1990s, a new trend of research on collaborative learning focusing on new technologies for mediating, observing, and recording interactions during collaboration has emerged known as computer supported collaborative learning (CSCL). It typically uses online networks for facilitating and recording online interactions among two or more individuals who may be geographically and/or temporally dispersed. In construction though there is a need to adapt the technology to improve the design and planning processes in a secure common data environment (CDE). However according to [6] there is a growing trend to design and develop integrated collaborative environment that allows project stakeholders to interact either Mobile, co-located or distant. CoSpaces Projects [7], an IST Funded Project by the EU shows how this concept could be achieved by using different technologies that provide different information richness (www.cospaces.org). In addition, collaborative tools help facilitate action-oriented teams working together over distant geographic locations, by providing tools that aid communication, collaboration and the means of problem solving.

Technology Integration is the use of technology tools in general content areas in businesses in order to allow stakeholders to apply computer and technology skills to learning and problem-solving. Collaboration requires individuals working together in a coordinated fashion, towards a common goal. Arguably Integrated Collaborative Technologies are those tools that can help stakeholders work collectively towards problem solving without considering geographical distance. These technologies could work either in a synchronous (real time) or asynchronous (not real time) manner, so allowing the stakeholders or the team members to share documents or files from anywhere at any time.

2.1 The need for collaborative working in railway tunnelling

A study [8] in 2008 mentioned that Network Rail (NR) was spending £433 million track maintenance and £1.305 billion more on track renewals, compared to its European peers. They argued that NR can unlock contractor efficiency contributions by a fundamental shift of supply chain relations based on the idea of competition and partnerships. They identified the main areas of improvement to be in planning, better use of possessions, standardisation of asset configuration and focus on quality of the asset condition. With a number of existing tunnel sections geographically distributed across the railway network, coordination of maintenance works is essential to deliver value for money. Crucial to the successful implementation of the strategy is the development of a collaborative culture (CC) and Integrated Data Management Systems (IDMS) throughout the supply chain to allow for better use of possessions and the design of new lines that connect to the existing infrastructure.

According to [9], despite the apparent lack of clear guide the process of collaboration between main contractor and subcontractor, project participants now realise that sharing of knowledge and information is a key element of a successful project delivery and contractual relationship. However [10] provided the strategy to improve collaboration to enhance organisational performance and project delivery through the management of process, people and data and wrote that, despite very strong willingness to collaborate, culture and awareness remain as significant barriers to adoption.

Rail industry leaders recognise the need for change. According to [11] wrote that the introduction of BS11000 in 2010 marked a step change in thinking for the UK rail industry led by Network Rail to encourage the adoption of CC whose benefits

had so far be limited to key programmes. Cross Rail, the biggest rail project in Europe has attributed success so far, in delivering the project with 42 km/26 miles of tunnelling to the strategy of adopting CC, through the supply chain under the NEC contracts on its 40 construction sites according to [12]. Cross Rail further adopted an innovative approach to data management for efficiency in project delivery, based on the principles of PAS 1192-2 as reported in [13].

Railway asset maintenance projects are delivered in a complex operational environment with various asset maintenance disciplines carrying out other works. The maintenance of railway tunnels is further complicated by limited working space, different tunnel designs and materials used. As a result, repair works are not straight forward but having the correct information at the right time helps in decisions about maintenance requirements. A collaborative approach to asset management could facilitate asset data sharing leading to a better understanding of the asset condition. This requires an integrated approach to asset data management that should standardise ways of working and data formats, used by stakeholders to the benefit of the industry. However, this must start with projects having sound data management systems that feed data of high integrity to asset data models.

2.2 Data Management in the rail sector (As-is)

Naturally, organisations have different ways of managing project data to deliver their objectives. According to [14] argued that during the project life cycle, vast amounts of data are generated by different departments in various formats and stored in many different places in an unstructured way. This occasionally leads to losses of data and time spent in unproductive searches.

Decisions on track sections due for renewal are made based on the data/information held in the asset management models like Maximo and the Ellipse for LU [13]. Keeping such models updated with accurate data is fundamental to accurately determine maintenance requirements and ensure adequate funding is available to optimise asset availability, essential for operating a safe and reliable train service. In the report [14] noted that maintenance of the railways is often undertaken with insufficient information and limited resources. According to [13] added that quite often deliverables in large rail infrastructure projects are not clearly defined. This may result in costly scope creeps and reworks in design and other preparatory works.

In addition to his report [14] it was added that railways rarely have enough resources to maintain the track asset at a level that ensures optimum operation of services. They are instead faced with prioritising maintenance actions to optimise safety and reliability. In a recent research about the future of digital railways, [15] wrote that railway operators are struggling to improve asset management, partly because the systems that generate and store data are not connected, even though the capability exists. The concept was affirmed by [1] who urged that in the recent times such levels of organisational intelligence are no longer a fringe concept but at the core of future investment decisions. This affirms the suggestion by [14] that the industry is finding that the solution to working more efficiently lies in using information technology.

The use of technology has enabled faster ways of data collection with gigabytes of data collected, often stored in many different places [14] and creating data silos. ABB's report [15] affirmed and wrote that, too often collected data is accessed by individual departments according to their needs, without a broader view allowing for the organisation to gain a full picture of their asset condition. This makes it difficult to analyse the generated large volumes of data together for effective decision-making about maintenance priorities.

In 2010 [16] and 2017 [2] wrote that project directors and senior managers of leading institutions are advocating for the adoption of common data capture and storage standards across all major projects to have a better understanding of the asset delivered. This can enable multiple-use of data across project disciplines/ departments. Further benefits can be achieved on the use of a single survey grid for geo-spatial data to enable designs to be overlapped and multi-use of data of fixed assets without the need for transformations or reworks.

2.3 Industrial responses

Cross Rail project adopted an innovative approach to data management in a common data environment (CDE) based on the principles of PAS 1192 series [13]. This was to improve delivery performance through better management of data/ information and facilitate structured asset hand over, ensuring that asset managers received reliable information critical to the safe and efficient operation and maintenance of the railway. With over 60 contractors and subcontractors on the project, the adopted method of information management in the CDE was developed in line with BS1192: 2007 and PAS1192-3. A new network consisting of 42 km of tunnels bored by giant tunnel boring machine 40 m below ground level was constructed. Tunnelling was successfully completed in 2015 having negotiated through various underground utilities and existing railway infrastructure.

Research done for NR recommended suggested that the increased use of mechanisation and better methods of data capture and storage. This would increase the accuracy of information generated about the condition of the delivered asset. Such information is later relied upon for effective decisions on maintenance requirements based on [8, 17].

Modern collaborative and data management approaches have mainly been limited to railway green-field sites. In the 2017 report [2] it was suggested that the railways brown field site could also benefit from the creation of the digital rail model from the existing information and maintenance processes. But, noted the challenge of incremental migration from the current, fragmented state to a single integrated model. A structured approach to data management can make it easier to manage job data files to reduce the use of different data, recollection of already existing data, using out of date data and ensure job closeout packages contain data of high integrity.

In addition in Greece—Attiko Metro announce for the Line 4 (new metro line) to use BIM files [18]. High Speed 2 project in the UK requested from their suppliers [19] to be BIM compliance. Though in Scandinavian Countries where BIM is well populated and applied it can evident show the use of BIM in planning stage [20]. Furthermore, it has to be noted that Heikkilä [21] noted that the use of BIM in tunnelling can add value in advancing intelligent information modelling; however, policy in Finland is not available yet. In contrary though Norway has HB138 that determines some basics for the BIM process of tunnels.

3. Research in collaborative working

The use of railways is forecast to grow about 50% by the mid-2030s [22] while the maintenance costs are said to be rising according to [23]. On the other hand, funding to increase capacity and maintain the infrastructure continues to be squeezed. Railway operators and asset managers are thus facing challenges to operate efficiently under tight budgets while transforming the old network to meet the future needs of an integrated transport network. Studies show that there is need for

change in the culture of the industry [8, 15, 22, 24, 25] and a number of performance improvement suggestions have been put forward. The emerging theme is that fragmented renewal projects need to change and adopt collaborative approaches that operate in CDE supported by technology to improve performance in planning, design, construction as-build data management and hand-back of projects delivered in a complex and fragmented railway sector. This will further impact on the asset data quality that is relied upon in making decisions about asset condition and maintenance requirements, and help improve future decisions on maintenance requirements.

Research in collaboration spans a number of incongruent fields such as organisational and social psychology, human factors, computer science, management science, education, and healthcare. In March 2009 the University of Nottingham, a partner in the European Funded project CoSpaces, published the attributes which influence and form part of collaborative work as well as developing an explanatory, descriptive model in order to enable a unified understanding of what it is to collaborate, and how best to communicate this to industry and to support collaborative working based on this understanding. The technique/method followed to check the validity of this research was semi-structured interviews with the CoSpaces user partners, and through drawing on the broad experience of working with a range of industrial organisations [17]. The main factors (individuals, teams, interaction processes, tasks, support, context and overarching factors) and sub-factors (with supporting references) give an overview of their relevance and importance to collaborative working. In addition, in order to assess how meaningful the factors in the model are, a series of card sorting exercises with human factors experts, took place. The study [17] showed that there was a general agreement on the main factors proposed for the model of collaboration. Moreover, groups of human factors experts reviewed the 27 different representational styles for a model of collaborative working, and incorporated the factors that had been considered during the card sort.

In particular, the external factors that influence building collaboration in a business environment and in a project are: trust, time, performance, management, conflict, goals, incentives, constraints and experience. The internal factors influencing the building of collaboration in a business are: teams, individuals, context, support, tasks and interaction processes. In order for external and internal factors to be applied during the project life cycle a number of different activities, behaviours and skills have to be developed.

The social behaviour of employees has a great impact on an organisation's effectiveness within the construction sector. Many aspects of social behaviour are manifested in project managers in interaction with team members. Moreover, working in teams magnifies and intensifies behavioural characteristics as a result of the close encounters that members have with each other, in terms of both formal and informal attitudes, where express responses/decisions are required for problem resolution. Proactive behaviour as a social behaviour impacts on project and organisational effectiveness [26] but the research in this paper show the need to explore and explain how project managers' proactive behaviour could be enhanced in a project.

In the paper [27] proactive behaviour was referred to as, "taking initiative in improving current circumstances; it involves challenging the status quo rather than passively adapting present conditions". In the paper [28] defined proactive behaviour as "self-initiated and future-oriented action that aims to change and improve the situation or oneself". As it is a relatively new field, there is no precise definition of proactive behaviour and current definitions are somewhat unclear and even contentious. Nevertheless, in recent times, a consensus appears to be emerging as to the definition of proactive behaviour, as suggested in [29]. Dictionary definitions

typically highlight two key elements of proactivity. Firstly, they identify an anticipatory element involving acting in advance of a future situation, such as acting in anticipation of future problems, needs, or changes. Secondly, the definitions emphasise taking control and causing change, for example: “controlling a situation by causing something to happen rather than waiting to respond to it after it happens”. In the paper [30] proactive behaviour is defined as “anticipatory action that employees take to impact on themselves and/or their environments”. In particular proactive behaviour has three key features:

- It is anticipatory—it involves acting in advance of a future situation, rather than just reacting.
- It is change-oriented—being proactive means taking control and causing something to happen, rather than just adapting to a situation or waiting for something to happen.
- It is self-initiated—the individual does not need to be asked to act, nor do they require detailed instructions.

The dynamic view of managing projects successfully is through enhancing the skills of the project manager in the manner of controlling and making more accurate decisions. With the increasing number of projects delivered in BIM environment, project managers’ skills must be adapted to suit. What is mainly needed in order to advance the project manager’s skills is the capability to interact with the other participants or members of the organisation or project to foster a collaborative culture. This interaction enhances the communication and the collaboration and develops the building of trust between the project manager and the participants. Estrin [31] stated that, “innovators must trust themselves, trust the people with whom they work, and trust the people with whom they partner, balancing their progress in an environment that demands both self-doubt and self-confidence”.

Communication constitutes conceptualising the processes by which people navigate and assign meaning and is an essential element of collaboration. Communication is also understood as the exchanging of understanding. Montiel-Overall [32] defined collaboration as “a trusting relationship between two or more equal participants involved in sharing thinking, shared planning and shared creation”.

In the research [30] supported the assertion that, in order to enhance trust, communication and collaboration, the construction of the following skills is required: anticipatory skills, change orientation and self-initiation skills. Henceforth, these skills will lead to the development of proactive behaviour. Therefore, a successful project manager/managers need(s) to be self-initiated, future oriented and anticipative. This behavioural situation will be used as the driving force that will initiate change in the operational and organisational system of a company. This approach will give an added value to the current state-of-the-art in project management. The proactivity concept assists project managers to think and act before, during and after a meeting takes place.

Moreover in paper [28] captured and analysed the proactive cognitive model. The model consists of proactive personality, job autonomy, co-worker trust, supportive supervision, self-efficacy, flexible role orientation (organisational commitment) and control appraisal.

The definition of each of the model’s elements is listed below:

- Flexible role orientation indicates the extent to which various problems affecting the longer term goals of projects would be of personal concern to an individual rather than to someone else.

- Co-worker trust refers to trust among the members of a project team.
- Self-efficacy refers to how confident a project manager feels in carrying out a range of proactive, interpersonal and integrative project tasks.
- Control appraisal refers to a belief that a project manager can control and have an impact on project outcomes.
- Change orientation refers to those project managers that have the intention of initiating/proposing changes in a project/task so as to optimise projects/tasks procedures and or performance(s).
- Job autonomy refers to the extent to which the project manager is involved in making decisions within the team.

	Project culture	Data governance	Technology
Key points	<ul style="list-style-type: none"> • Individual skills and behaviour • Individuals in teams with complementary skill sets • Aligned individual/team goals with that of organisation • Interaction of individuals in teams and departments • Trust and experience • Suitable working environment • Coordination • Effective communication i.e. verbal, electronic 	<ul style="list-style-type: none"> • Legislation • Data policy • Grid definition (geo-spatial and CAD) • Data quality assurance • Data storage and sharing • Defined working area • Published data/information area • Data shelf life • Control of updates 	<ul style="list-style-type: none"> • LAB • IT tools • Common data environment—e.g. Bentley AssetWise, Bentley ProjectWise, SAP, Livelink, Asite • Access rights • Editing rights • Communication e.g. Skype, emails, notifications
Supporting frameworks or standards	<ul style="list-style-type: none"> • ISO44001—Institute of Collaborative Working, CRAFT model • CoSpaces Integrated Project • Four Ways of Collaboration 	<ul style="list-style-type: none"> • ISO9001 Quality Management • Railway industry standards • Guidance of data management—IGGI 	<ul style="list-style-type: none"> • ISO 19650 and PAS 110092 series
<p>Integrated project collaborative environment Collaborative culture—cooperation (clear definition of scope and deliverables) Integrated data management system—(one source of truth for design, construction and handover data) Lean construction—(elimination of wasteful activities through better coordination, planning and scheduling) Process (BIM)—holistic approach to asset data management and asset maintenance</p>			

Table 1.
 Requirements for a collaborative environment in railway asset maintenance projects.

- Proactive personality refers to the relatively stable tendency to identify problems in advance.
- Supportive supervision refers to the enhancement of leader effectiveness in a self-management context.

What can be gathered from the above is the need to focus on low project information maturity in order to enhance the progress of a project. The use of BIM and supporting tools then ensures that project information is of the right quality and shared from a CDE so that team members access the same information. The proactive project manager's behaviour aids in developing project information maturity to deliver the project that meets the client's requirements. The added value is that more evidence based higher quality of decisions will be made and the delivery team will have better control of the project through its delivery and operational life cycle.

There is consensus that collaborative approaches are part of the solution to improve project performance. However, as highlighted in the definitions of collaboration [33] and interpretations, the words collaboration and partnership are often used interchangeably making it difficult to have a clear meaning and difference between them. Despite the concept being widely used, there is no clear understanding of what collaboration is [17].

The complexity of collaboration in the rail industry can also be seen from the procurement perspective, where partnerships in various forms seem to be the preferred option in track renewal projects [33, 34] and presumed to be working collaboratively. Collaboration has been seen to improve project performance and its effectiveness can be enhanced through support from good technologies [17] and processes to further add value in the delivery of renewal projects.

The adoption of CC supported by technology in railway asset maintenance projects using IDMS in a collaborative environment can no-longer be ignored in the search for solutions to lower maintenance costs, deliver value for money and provide efficient services, in the face of shrinking budgets. Further, it will facilitate the integration of the UK transport network to provide future customers a first class travel experience of connected means of transport supported by Big Data. **Table 1** shows the requirements for collaborative environment in renewal projects that must be supported by Senior Management and a suitable form of contract/procurement process based on a track renewals case study.

4. Technology in tunnelling construction

The project data must be kept in a secure environment with set permissions in order for stakeholders and project team members to have access from anywhere at any time. In order to achieve this then a common data environment (CDE) needs to be set up. In this environment all project data need to be correctly labelled based of standard file naming conversions form the ISO 19650 standard. This makes searches using metadata easier and saves time wasted on unproductive searches. Having easy but secure remote access also allows for further (project) data analysis that can help to pre-identify any project activities that provide more information about who is involved in the projects (Organisation Breakdown Structure), what each person is expected to deliver (Work Breakdown Structure) and what the cost of each activity is (Cost Breakdown Structure). All the captured and updated data might be used for further analysis with the aim to support any decisions before, during and after

completion of the project. Such data analysis could support investor(s) capacity to understand based on evidence whether it is worthy to progress their project idea as well as to pre-identify any risks that can be evaluated in consideration of other factors that may affect the project such as in any political, economic, social, environmental, legislation, technological and sustainability issues.

Data used in tunnelling projects is collected using many different tools such as Laser Scanner, Sensors, inspections, etc., and comes in various formats. All these data sets could be available to stakeholders synchronously i.e. either in real time or not. With the increase in analytical tools for infrastructure maintenance, Big Data analytics is an increasingly area in construction sector due to high Volume, Value, Variety, Velocity and Veracity generated through the project whole life cycle. Concerns in copyrights for cloud based data and BIM models are beyond the scope of this book. In addition the power of the Internet of Things (IoT) as a network of physical devices, vehicles (suppliers), and other project materials embedded with electronics, sensors, software, actuators and connectivity enables construction asset/building objects to connect and exchange data too.

The power of visualising information using integrated collaborative environment that uses software such as Autodesk Revit, CADduct and Tekla, Navisworks, Solibri allows stakeholders and team members to understand coherently and stimulate any problem when it occurs. Among the core project challenges, AEC industry faces the lack of sharing of information and cooperation in the development of processes to improve efficiency in the delivery of construction projects.

This is mainly what BIM is renowned for and is the reason why the BIM integrated environment requires further development in the construction industry. Kapogiannis and Sherratt highlight the need and impact of collaboration culture in the architecture, engineering and construction sector.

Considerably the knowledge about BIM and the higher levels of maturity requires further development of processes aiming to improve construction efficiency through automation. Tools that could help to support and enhance knowledge to humans are by teaching machines using Artificial Intelligence and Machine Learning. This idea could go further down to simulate a process and/or an event in a project, for example delivering materials from suppliers or using a robot to paint a wall fairly quickly within cost budge. This can also help stakeholders to generate new business models.

The regular review (Decision) of models and management of associated stage deliverables using information exchange platforms such as COBie to the employer is a key aspect of the BIM process. The employer should ensure that the Exchange Information Requirements (EIR) are defined and agreed in the procurement stage of the project, in a collaborative environment.



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Project meetings undertaken in collaborative environments allow key stakeholders to determine, understand, analyse and review the design models in 3D and other outputs, provide their feedback and validate the stage PLQs. Ideally there should be three key stages to the process:

1. Before review meeting,
2. During review meeting,
3. Post review meeting.

This workflow allows the team to develop a proactive behaviour whilst collaborating and sharing key projects/asset data and information. Check more on BIMPortal of the Scottish Future Trust [34].

For project delivered in high levels of BIM maturity, such review meetings are normally undertaken in a virtual environment using a projector (as illustrated below) or on larger projects using virtual mock-up facilities, such as CAVE (Computer Assisted Virtual Environment) and or immersive lab often available at local universities or further education colleges.

5. Benefits and challenge of the use of BIM

In a survey of 1000 active BIM users in the UK the NBS [35] concluded that BIM was a useful strategy in achieving goals of the construction strategy 2025 as it brings cost effectiveness and reduce time from inception to completion. This conclusion was supported by the fact that 70% of participants believe that BIM reduces overall project cost including initial cost of construction and the whole life cost of built assets. Another 60% agreed that BIM reduces overall time, from inception to completion, for new build and refurbished assets and helps to meet the target of 33% reduction in initial.

- Eliminate costly and timely traditional construction mock-ups
- Different design options and alternatives may be easily modelled and changed in real-time during design review base on end users and/or owner feedbacks
- Create shorter and more efficient design and design review process
- Evaluate effectiveness of design in meeting building program criteria and owner's needs
- Enhance the health, safety and welfare performance of their projects (for instance, BIM can be used to analyse and compare fire-rated egress enclosures, automatic sprinkler system designs, and alternate stair layouts
- Easily communicate the design to the owner, construction team and end users
- Get instant feedbacks on meeting program requirements, owner's needs and building or space aesthetics

But still the biggest challenge is not the use of the aforementioned technologies in a project process but to change the way of thinking by engaging team members. Research shows the significant impact of gamification to support engagement. The potential impact of the use of gamification in construction projects is to change the behaviour of stakeholders and motivate them for better performance through the triggering of their social skills. In our days many enterprises use gamification in order to enhance the collaboration and communication between their employees.

A recent study published by CITB (Construction Institute Training Board) indicates that in the UK, the construction industry will grow by almost 3% and create many job vacancies due to the need of collaboration over the next 5–10 years.

Building information modelling provides the construction industry with an environment and framework for great coordination and integration of people and processes through an open sharing of data and information. A BIM environment comprises of computer-aided design tools that can a better understanding of design and construction sequences through a virtual representation of the built asset so that the construction team and owners and operators can take part in detecting and resolving conflicts in a proactive fashion.

On project delivered in BIM environment, the Client has a strong influence on the extent, effectiveness and efficient use of BIM. Client may also be motivated by short terms goals such as using virtual reality to improve acceptance of the project scope by decision makers. While adoption of BIM for mega projects is likely to generate an advantageous returns on investment, for smaller project a decision on the use of BIM should be made based on the appropriate level of maturity after a careful considerations of cost and benefits. Perhaps the use of BIM on projects should be made on grounds that BIM will be implemented to meet long-term goals in case there are several projects are forthcoming to outweigh the initial investment. It is likely that cost invested in a lifecycle BIM toolkits will be paid back via cost reduction from intelligent operations of the built asset, modernised ways of working that improves service delivery or increasing global competitiveness. BIM has been recommended by designers who already are familiar with it. Clients are likely to maximise benefits of BIM if its use is extended to include asset management and compatible software are in place.

The RIBA plan of work 2013 stages provide for an overlap with BIM tools.

- Stage 1. BIM can be adopted at any stage within the asset development process but to benefit more from BIM, it would be useful to formalise BIM mandate at the strategic definition or inception. When decision to incorporate BIM is made as early as RIBA stage 1 client gets an adequate time to prepare requirements and resources that will facilitate aligning BIM with asset management systems when the project is completed.
- Stage 2. BIM integration strategy will be developed and tried in the concept design stage so that a functioning BIM environment is created. In the concept design stage BIM strategy should be developed to provide an environment for project integration. The strategy will identify the extent to which BIM will be used. It should also assess BIM capabilities in terms of expected product outcomes, required trainings, communication channel, roles and responsibilities and BIM tools. The use of performance-based BIM specifications focusing on product outcome has an added advantage over prescriptive requirements for software. BIM will be used by the lead designer as design tool and to communicate design solutions with project internal stakeholders to facilitate decision making.
- Stages 3–4. A fully integration of BIM is possible during the developed design stage which is characterised by increased in information exchange between the designers and quantity surveyors. A virtual value engineering process will simulate design solutions for cost affordability. Consideration of design options can benefit from visual models shared for analysis and risk reduction. Multidisciplinary 3D geometric models can be shared with others designers and the construction teams through a shared BIM environment so that

buildability issues and impact to the environment can be assessed. Due to the number of exchanges in a coordinated design, high level of design agility can be attained by rapidly adopting changes from peer reviewers and on so doing a design development cycle time can significantly be reduces.

- Stage 5–6. By taking on board all the information modelling then contractor and the supply chain start and manage the construction—building process in an efficient way where tablet and mobile technology could the team could manage the control process, quality assurance, productivity, efficiency, buildability etc.
- Stage 7. ‘As-constructed’ Information updated in response to ongoing client feedback and maintenance or operational developments.

An integrated BIM environment is a virtual workplace that creates a common data environment (CDE) to facilitate an efficient and two-ways exchange of data and models. **Figure 2** is an input process output model illustrating a BIM environment. The most important input for an integrated whole life BIM integration is client’s information requirement which brief the project team needs of the client and how they will align BIM to post project operations. Input data from fully dimensioned 2D and 3D geometric models from designers can be pushed to other specialist designers or the construction teams for feedback or inputs with a reduced risk of data loss.

The first step in implementing BIM in a project basis is for the client to develop an outline BIM strategy at the inception stage in collaboration with the project consultants. The client will prepare a statement, which will form the basis for appointing both the designers and contractors. This statement is referred to as Employers information requirement (EIR) that clearly explain why BIM should be used, its drivers and commitment and capability of the client to collaborate in a BIM environment. Where adoption of BIM is decided upfront, client must make the expectations known before appointing the lead designer. The client will also specify technical information software platforms that align with existing or recommended facilities management software. This has been confirmed though through [26]

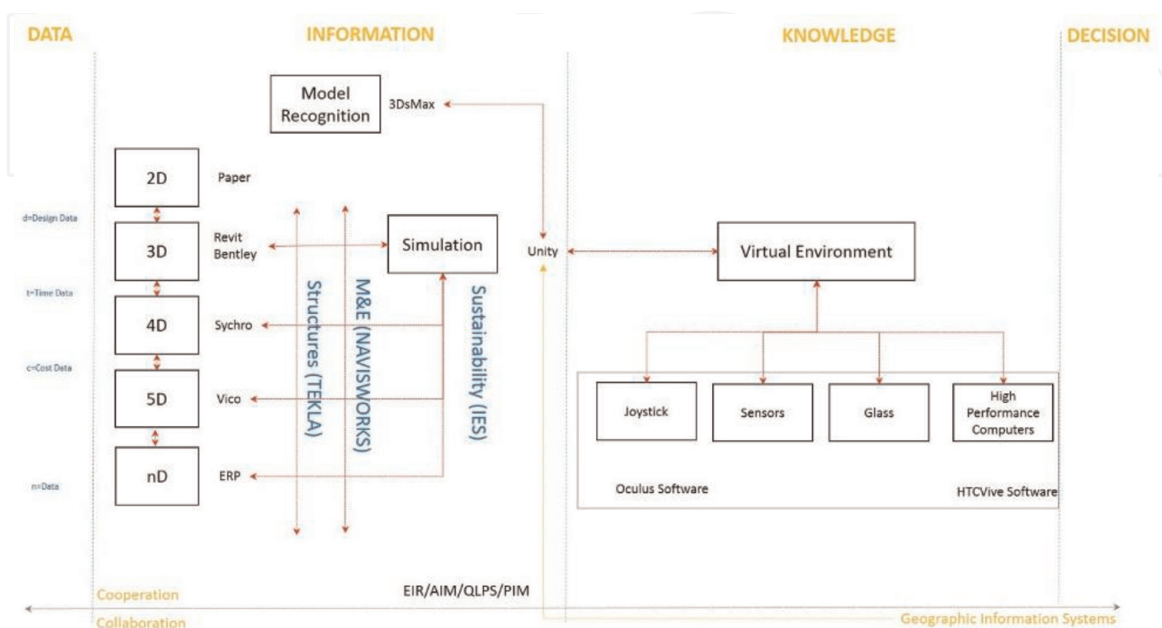


Figure 2.
 An integrated collaborative environment © Kapogiannis, 2018.

where researchers shown the added value of BIM in Facilities Management in the hospitals by integrating technologies incorporating 3D modelling and beyond. Using performance based technical specifications empowers designers and contractors to come with most efficient and cost effective solutions to meet the EIR. Prescriptive requirements such as software vendors will force the supply side to incur additional costs of retraining for compliance. The EIR will also stipulate roles and responsibilities including for platforms that will be shared by several parties. It is crucial that management issues are covered in the mandate given to the project manager or BIM manager. The mandate will specify the protocol to be adopted, how information will be secured, system performance, how coordination and will be achieved and issues of ownership. At this stage it will be useful to specify if models will be part of deliverables to be used as part of tender documents.

The NBS protocol defines BIM execution plan as a response of designers and contractors to the employer's information requirements (EIR). It will be prepared as part of the project implementation plan in the pre-contract stage and will be updated after the contract is signed. The pre-contract execution plan communicates the approach to data exchange and confirms the ability the designer or contract to meet expectations of the client.

It is inevitable that a huge volume of information will exchanged through several iterations of value engineering taking place during the design and as the work commences on site. A typical design process will include internal and external peer reviews and approvals from the client. The iterative process will assure the client that the final design is optimum and guarantees good value for money. To streamline communication of information during the design and construction process the project manager will develop and maintain a master information delivery plan (MIDP) which services similar purposes as a communication plan with the focus on information exchange with main collaborators. Although the responsibility of is with the project manager but this is a collaborative document and it should be developed jointly with managers leading the design, construction and procurement. The plan answers information exchange questions such as who is creating a 3D model, when it will be prepared and based on what procedures. The plan must be specific on the deliverables including models, drawings, specifications and whether they will form part of the tender documents to be distributed to bidders. A more detailed execution plan will be agreed by a team of designers and other consultants post-contract. The information delivery plan will be incorporated in the post contract execution plan setting out a strategy for delivering technical design information as well as management reports.

6. BIM standards and contracts

BIM can adopt an information system that promotes a single point of truth to leverage information exchange in a spirit of collaboration and open sharing. However, it is important to emphasise that the collaboration process will involve multidisciplinary teams such as technical designers, cost consultants, facility managers, planners and other reviewers, each of them using a different software platform and are based in different geographic locations. A typical example would be a 3D geometrical models produced by the Architect. The model will be peer-reviewed by other designers before the final approval by the client. It may also be modified by other users when a clash is detected. Information exchange in a BIM environment is likely to lead to series of issues. It is now possible to adopt a BIM integrated system that supports multi applications. Another challenge will be multiple users modifying the model concurrently thereby creating version conflicts. A lockable BIM integrated system is preferred in this case to reduce conflicts and residual data loss.

The exchanged data and models are often large files and if shared using internet based technologies may results into speed and security issues which the adopted BIM system has to revolve proactively.

Considering the fact that procurement strategy and its contract is the key to operate a construction project then BIM might be a new swift that could in the future affect also the way of bid—tender relationship and its management. Crawford and Stephan [36] mentioned the “ultimately also the opportunities BIM offers in revolutionizing the way projects are procured in the first place”. The below diagram (**Figure 3**) picks up on some typical processes associated to BIM that can be applied across different contract procurement methods.

Furthermore there are the following protocols are required to be followed in BIM Level 2 according to Digital Built Britain 2018 [37].

PAS 1192-6 specifies requirements for the collaborative sharing of structured H&S information throughout the project and asset life-cycles. This PAS standard supports the development of structured H&S information for all construction projects progressively from the outset.

PAS 1192-5 specifies requirements for security-minded management of BIM and digital built environments. It outlines the cyber-security vulnerabilities to hostile attack when using BIM and provides an assessment process to determine the levels of cyber-security for BIM collaboration which should be applied during all phases of the site and building lifecycle.

ISO 19650-1 (former BS 1192:2007 + A2:2016) provides a ‘best-practice’ method for the development, organisation and management of production information for the construction industry, using a disciplined process for collaboration and a specified naming policy.

ISO 19650-2 (former PAS 1192-2:2013): the requirements within PAS 1192-2 build on the existing code of practice for the collaborative production of architectural, engineering and construction information, defined within BS 1192:2007 + A2:2016.

PAS 1192-3 provides guidance to Asset Managers on how to integrate the management of information across the longer term activity of asset management with the shorter term activity of asset construction for a portfolio of assets.

BS 1192 4 outlines the UK usage of COBie, an internationally agreed information exchange schema for exchanging facility information between the employer and the supply chain.

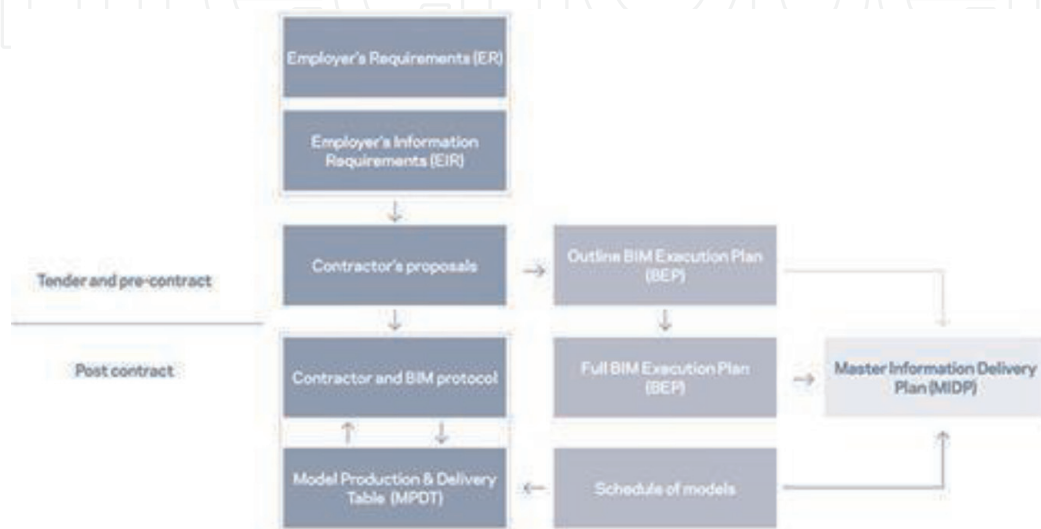


Figure 3.
 BIM execution plan (BEP)—procurement process adopted by ISO19560 1 and 2.

BS 8536-1:2015 gives recommendations for briefing for design and construction, to ensure that designers consider the expected performance of a building in use. The standard applies to all new buildings projects and major refurbishments. Also aims to (a) involve the operator, the operations team and their supply chain from the outset and (b) extend the involvement of the supply chain for the project's delivery through to operations and defined periods of aftercare. The scope of the revised BS 8536-1 has been expanded to include briefing requirements for soft landings, building information modelling (BIM) and post occupancy evaluation (POE).

BS 8536-2:2016 is part of the BIM level 2 suite of documents developed to help the construction industry adopt BIM. It gives recommendations for briefing for design and construction in relation to energy, telecommunication, transport, water and other utilities' infrastructure to ensure that design takes into account the expected performance of the asset in use over its planned operational life. It is applicable to the provision of documentation supporting this purpose during design, construction, testing and commissioning, handover, start-up of operations and defined periods of aftercare.

PAS 1192-2R—specification for information management for the capital/delivery phase of construction projects using building information modelling and PAS 1192-3R—specification for information management for the operational phase of assets using building information modelling are in due in 2018.

ISO19650 1:2018 organisation and digitization of information about buildings and civil engineering works, including building information modelling (BIM)—information management using building information modelling—part 1: concepts and principles.

However there are also content, digitization, interoperability and collaboration that are figured in different maturity stages that could enable new business models in BIM and beyond. According to European Union Report [38] the levels are presented in **Figure 4**.

The above has been applied in the United Kingdom on the basis of keeping consistency among content, digitization, interoperability and collaboration in different maturity level during the project management life cycle. Moreover if is

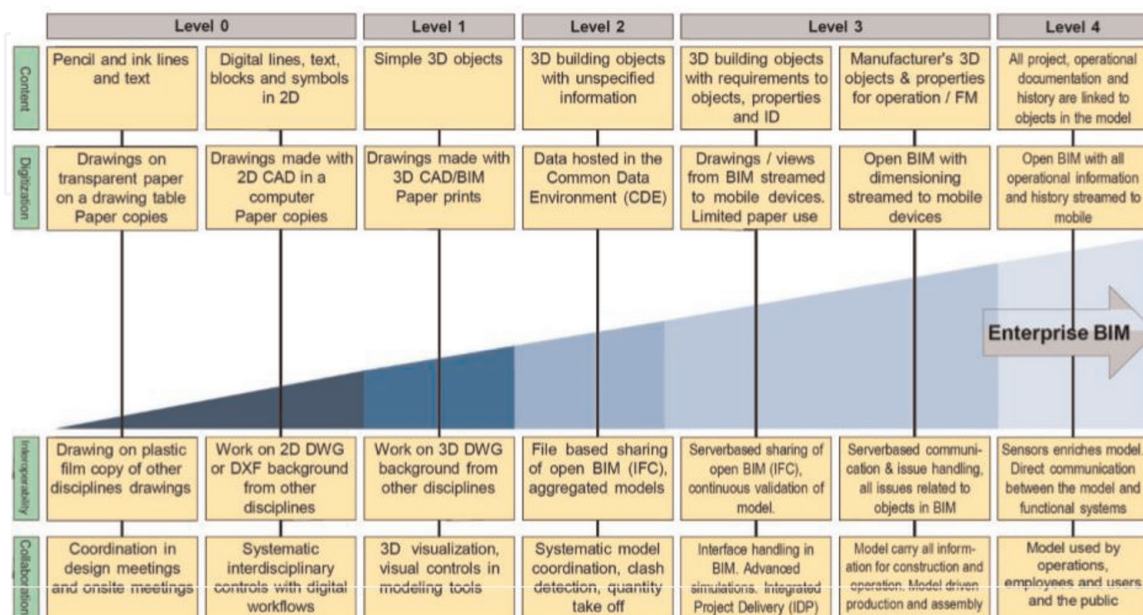


Figure 4. BIM maturity level adopted by building information modelling (BIM) standardisation Martin Poljanšek (2017).

required to see from its global implementation perspective according to Autodesk Resources [39]:

The European Union Public Procurement Directive in 2014 encouraged all member states to adopt BIM to increase value on public projects; The UK BIM Mandate will be in force in the Spring of 2016 for all centrally funded public projects in England; France have appointed a Digital Construction lead for the Ministry of Housing and announced a National Digitisation Plan including promotion of BIM; Germany's Construction Reform Commission has established a BIM Working Group to develop a BIM strategy for Germany and increase BIM adoption on projects; Austria has a published National BIM Standard. Though in infrastructure the Environment Agency (EA) in the UK is determining its supply chain BIM data requirements throughout project delivery; Highways England is running a number of BIM pilot projects to improve design coordination, project team collaboration, stakeholder engagement and project delivery; Finland's road authority has stipulated supply chain data submissions will be in LandXML InfraModel 3 (a structured data format for civil engineering) to enhance asset data records and The Swedish and Dutch transport agencies (Trafikverket and Rijkswaterstaat) have initiated a European Commission funded project 'V-Con' on BIM for roads standardisation and implementation.

The importance therefore in the use of Digital Construction in Architecture, Engineering and Construction (AEC) forces the education to adopt similar strategies into the curriculum [40].

7. Future of tunnelling construction

CoSpaces is an IP project funded by the EC under the IST Programme of the FP6, which has the overall objective to develop organisational models and distributed technologies supporting innovative collaborative workspaces for individuals and project teams within distributed virtual manufacturing enterprises. Thus, the use of CoSpaces and similar technologies for tunnelling construction projects will enable effective partnerships, collaborative working culture, promote innovation, improve productivity, reduce the length of design cycles and take a holistic approach to implementing production phases. Example: Video 1 available from (can be viewed at) <http://cospaces.org/demonstrators.htm>

This will be achieved through enhanced human communication, innovative visualisation, knowledge support and natural interaction and will transform the current working practices to be more competitive in the global market. CoSpaces proposes to validate these collaborative workspaces against three sectors: aerospace, automotive and construction. However, the impact of the technology will go beyond these three sectors due to the generic nature of the technologies. CoSpaces will undertake the ambitious challenge of developing the technical, organisational and human networks to build collaborative workspaces. This will be achieved through a systematic and integrated programme of RTD activities, dissemination, training, demonstration and exploitation activities, led by a consortium of European experts who are committed to this mission.

8. Digital construction and businesses

Additional reason for the use of digital technologies is to support an integrate processes and different industries in a way to meet clients' requirements. This integrated environment will allow stakeholders to share data, information and knowledge in a way to be efficient and effective during the project life cycle even

when the product is in use. It is generally accepted that the client would be benefited by the use of advanced design and construction methods by understanding holistically how the final product would like. Henceforth, it will be easier to make any alterations in early stage and/or to assure that the product will be reusable in the future. Studies show that the impact of integrated collaborative technologies on team collaboration is to form a collaborative culture in all stages of construction projects. This collaborative culture allows stakeholders to use these technologies to enhance team collaboration. For example, (virtual) meetings could help to pre-identify clients' requirements, hidden costs and project risks during all stages of the project that are needed, to be proactive. Moreover, stakeholders in this collaborative environment will have the capacity to design a competitive procurement strategy. This strategy will help them to run the project smoothly, eliminating risks and mapping clients' requirements to projects output and outcomes too. Beyond the added value of running virtual meetings and designing a competitive procurement strategy, the collaborative culture allows stakeholders to improve accuracy, sharing and access to project data and information remotely at any time, enhancing well-being and productivity. In addition, the collaborative culture can assist to develop trust among stakeholders and improve the control all project stages. So, considering that a collaborative culture could be generated by stakeholders to improve the design, delivery and hand over of a project through collaboration, then it is also required to identify how project performance could be improved.

9. Chapter summary

As it can be seen the application of BIM and digital construction in tunnelling engineering is vital in order to ensure consistency among content, digitization, interoperability and collaboration in different maturity level during the project management life cycle. Moreover to establish a collaborative culture enabling the next generation of tunnel project and asset managers. In addition, smart tunnels could support the society and make accessible communities where people are able to improve day-to-day life significantly.

10. Case study

10.1 TfL's BIM application on a tunnel relining project in an operational environment

Building information modelling (BIM) is a complex business process that has the potential to enable asset owners to achieve better control over their projects and assets, offering benefits throughout the asset life cycle. Many governments are now demanding that large public facility agencies adopt and implement BIM to improve delivery performance of the construction industry. Some governments have published BIM guidelines with most of these being technical specifications that are useful at the project level, but provide little support for the organisation-level adoption effort [31].

In the UK, the government published the 2011 Construction Strategy that mandated the adoption of BIM to BIM level 2 by April 2016 for centrally funded projects. Although not publicly funded, Transport for London (TfL) adopted BIM to deliver some of its capital investment projects. An example of BIM application at TfL is the award winning Bond Street to Baker Street (BS-BS) tunnel relining

project. This project was delivered in an operational environment, safely, ahead of schedule, under budget and with minimum service disruptions.

Transport for London (TfL) is an integrated transport authority that controls the day-to-day running of the metropolitan public transport network, which includes the London Underground (LU) railway. To provide a structured approach and guidance in the implementation of BIM, TfL has developed a suite of BIM documents for use by project teams delivering infrastructure projects.

The increasing population of London and the rising demand in railway usage demands an efficient transport system with minimal impact on the environment that allows for commuters to travel safely at affordable fares [31].

The LU network consists of 402 km of tunnels, which are a mixture of cut and cover sections and deep tube. Since the underground opened in 1863, London has been and continues to be shaped and influenced by its transport system, which is at the core of the city's economy. The LU lines are heavily used and some operate on ageing infrastructure (Mayor of London, 2015). Strategic network expansion is fundamental to meeting future demand and so is the need to keep existing infrastructure in good working order.

Strategic plans to deliver station capacity, signalling and rolling stock improvements are continuously reviewed, planned and delivered to minimise both disruption to the public and businesses and impact on the environment. It is also critical that the existing infrastructure is adequately maintained concurrently with the construction of capacity improvement projects. In the modern built environment where transport networks often use underground tunnels for transport networks, construction and maintenance of the tunnels is challenging and can be highly disruptive.

BIM processes, supported by advances in digital engineering techniques, are now making it possible to plan, design, build, operate and maintain cost effectively with minimum disruption. For built assets, the challenge is how to make use of the existing record information to support data driven asset management systems. The BS-BS tunnel relining project highlights the challenges of undertaking tunnel maintenance/repairs whilst maintaining the existing service. The use of BIM was fundamental in assuring stakeholders that the tunnel lining repair works could be delivered safely, on time, on budget and without impacting the train service.

Asset management processes could benefit from the rapid advances in technology that are increasing the capacity to handle large volumes of data at lower costs. The development of quicker data analysis tools and Artificial Intelligence (AI) are increasingly making data management the core of strategic planning for organisations [10] and influencing change towards data driven asset management. BIM adoption will help improve the quality of data in the asset information models and allow for predictive maintenance and ultimately lower maintenance costs.

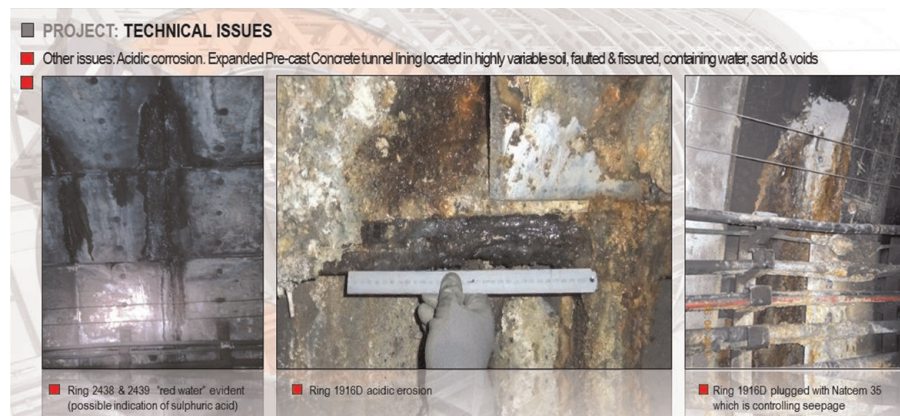
LU is one of the oldest and most complex rapid transit rail networks in the world, with up to 5 million passenger journeys a day for the local population and business commutes. A strategic approach to asset management as guided by the ISO 55000 series is fundamental to asset performance. Periodic inspections of assets help detect deterioration of the asset condition and are used to inform decisions about remedial action required. With the increasing understanding of BIM, its application for asset management could contribute to reduction in maintenance costs and help organisations like TfL continue to provide affordable public transport.

Tunnels used for rapid transit systems are generally constructed using the cost effective cut and cover and rock tunnelling methods. Cut and cover tunnels in the built environment are more disruptive than the deep bore tunnels and have major

logistical challenges during construction and maintenance. Deep tunnels are more vulnerable to water incursions that may weaken the new tunnel structure. Limited space in the tunnels also makes it difficult to undertake maintenance tasks and major repair works often require the tunnel sections to be closed for long periods of time. For rapid transit systems, this can result in major service disruptions that can attract negative publicity and political pressure.

The award winning tunnel relining project of the 215 m section between Bond Street Station and Baker Street Station is an example where BIM delivered real value for TfL. Information used in this Case Study is based on data collected from company records relating to the specific project.

Constructed in the early 1970s using Expanded Pre-cast Concrete (EPC), defects on the single bore southbound tunnel section between Bond Street and Baker Street were first noticed in 2000. Tunnel monitoring and extensive investigation identified that acid in the ground water and the desiccation of the surrounding clay regions had weakened the tunnel section, causing EPC segments to crack and the tunnel to lose some structural integrity. This increased the risk of water ingress and partial collapse of the tunnel which may have resulted in the partial closure of the line for a long time.

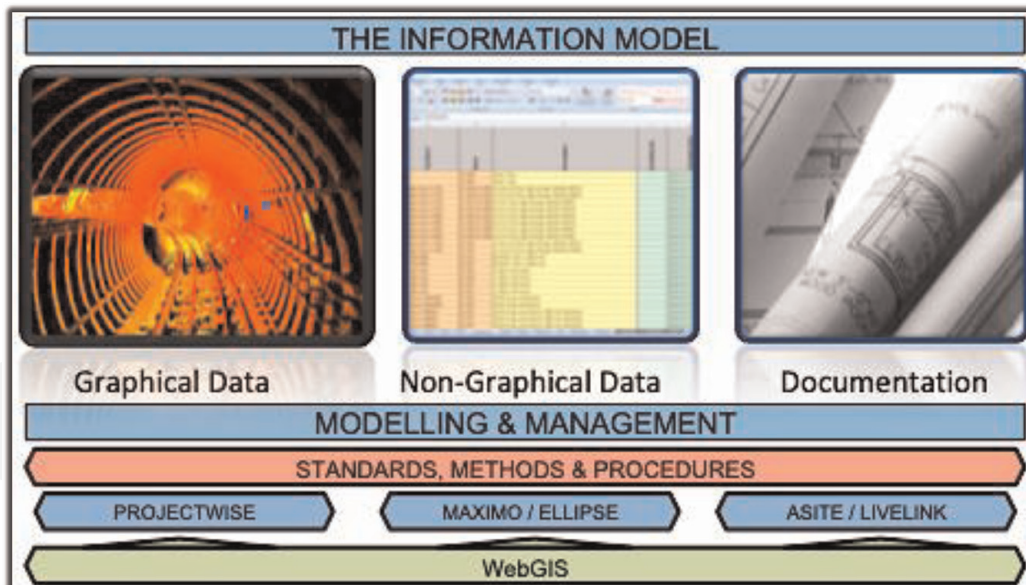


Closing the line would have had a huge impact on the transport network, disrupting TfL and businesses in the local area. Local repairs and comprehensive tunnel support works were carried out to make the tunnel safe while a long-term solution was considered. The decision was taken to reline the tunnel while the line remained operational and BIM was to be used to improve the delivery assurance of this challenging project. The key objectives for the project were to deliver the project safely, without affecting running the full service of 30 trains per hour on the line, to the agreed time line and cost.

10.2 BIM application

BIM processes, based on standards available at the time i.e. BS1192-2007 and PAS1192-2: 2013, were used to manage the information needed to design and repair the tunnel section.

Collaboration between teams involved in the project was instrumental to the successful delivery of the project as it allowed for standard methods and procedures for the production, storage, sharing and use of project data to be agreed early. A common data environment for graphical data, non-graphical data and documents was established as shown in **Figure 1**, to provide a single source of project data.



BS-BS project information requirements were defined early from the asset inspection records and helped the project have a clear and detailed scope. The project was delivered internally and it was the first time of doing this kind of work in an operational environment. Outsourcing the work would have been a challenge as it would have been difficult to define the scope for contractors and find the one with relevant experience. To minimise the risk a key objective was set to prove that the project could be delivered before site works began. This required design solutions for tunnel repair and plant together with the delivery plan to be developed and tested virtually as proof of concept.

The existing asset records for the project were in an analogue format and were not able to help create a 3D design model. So, laser scan surveys were conducted and the resulting point cloud data was used to create a 3D model of the existing tunnel. This was stored in Bentley ProjectWise, which provided a single source of graphical project data (**Figure 5**).

Using the survey model, 3D, 4D and 5D models were created. The 3D design model was used to design modifications of the train used for transporting materials and equipment to site and to develop bespoke equipment used to install prefabricated tunnel segment rings. The modified train was also used to remove waste material from site, as there was no room for on-site storage (**Figure 6**).

Most of the work was carried out at night when trains are not running, to minimise service disruption. The shifts had a typical on-site working window of 2.5 h

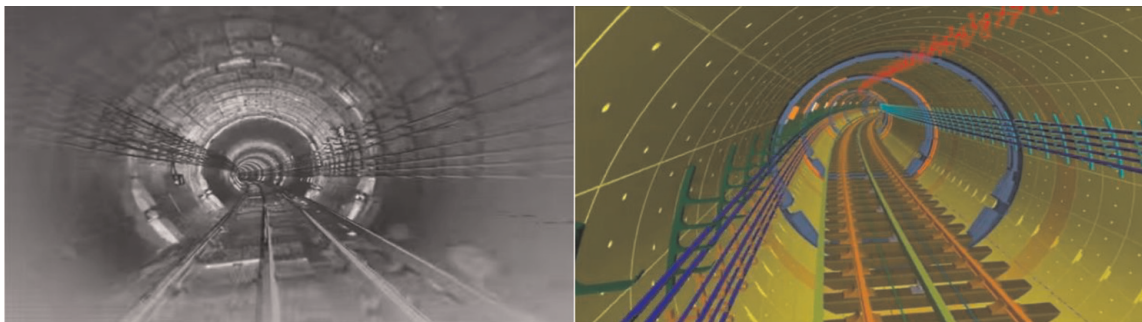


Figure 5.
BS-BS laser scan survey and 3D design model.

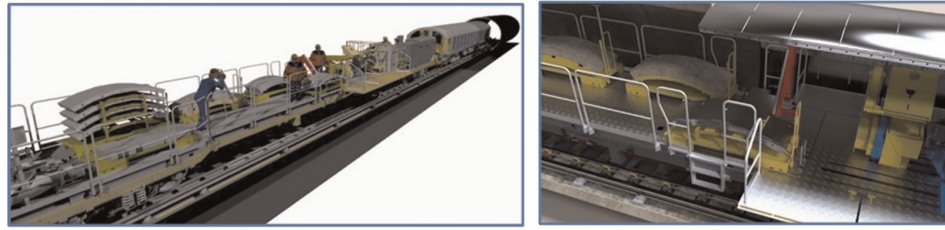


Figure 6.
Model of BS-BS train. Source: <https://www.youtube.com/watch?v=eN2MBIfhxBI>

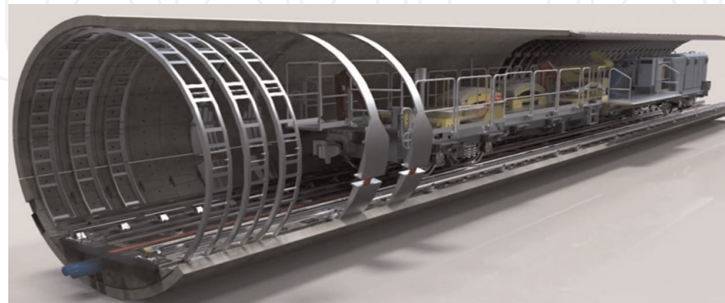


Figure 7.
BS-BS 3D model of train in the tunnel.

and the modified train with working platforms and carriages for carrying waste materials solved a major logistical problem and helped maximise output on-site.

A virtual reality model was created and used to demonstrate constructability of the project and was instrumental in convincing stakeholders that the project could be delivered against the set objectives. It was further used for virtual training of operators before they went to site, to improve safety (**Figure 7**).

10.3 Project outcomes

The design was completed and tested virtually before construction work started. This allowed the project team to plan and schedule tasks using 4D model and reduce delivery risks. Planning using the 4D model contributed to the successful delivery of the BS-BS project and meeting the key objectives of being delivered safely and without affecting the travelling public.

On completion in May 2015, the BS-BS project was delivered at £2 million below the initial budget of £34 million and 4 months ahead of schedule. The renewed tunnel now requires minimal maintenance and lessons learnt from the project will be passed on to future projects.

Key to the successful delivery of the BS-BS project was the implementation of BIM. BIM enabled better coordination of the project that enhanced the health and safety planning of such a complex project throughout the project life cycle. Lessons learnt from the project will be used to improve the delivery of similar projects using some of the tools developed for the project.

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