A state-of-the-art review of Network level bridge management systems and proposal of new approach for predictive maintenance

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Abstract

Rapidly changing climates and increased traffic significantly impact on the health of structures in our road network. Catastrophic failures are becoming increasingly common; Northern Ireland alone witnessed 5 bridge failures in August 2017. In a time of reduced government funding and uncertain European support, a transfer from the current reactive-based method of maintenance to more reliable predictive capabilities is critical. An investigation into bridge management systems across the UK road network identified alarming disparities. Existing systems are focused specifically on the collection of data, rather than interpretation. There is little consideration given to the interdependency of assets and the cascading effects of changing traffic patterns and extreme incidents, such as flooding, bridge collapse, terrorist attacks. This paper provides a review of the current bridge management systems in operation including details of a number of current research based system developments. The paper introduces a potential new approach to bridge asset management which will be implemented across the Northern Ireland road network in collaboration with the Northern Ireland Department of Infrastructure.

Keywords: Asset Management, Bridge management systems, Digital Twin

Introduction

Asset management is a term commonly used to describe a system of processes which are designed to achieve optimum management of assets(Amadi-Echendu *et al.*, 2010). For complex infrastructure systems this includes balancing maintenance, operation, economics, finance and engineering principles in order to achieve value for money through sustainable and functional solutions (Parlikad and Jafari, 2016). The UK's largest, most valuable and visible assets owned by the public is the Highway infrastructure. In 2013 The Highway Infrastructure Asset Management Guidance Document (HIAM) was published to provide the basis for a consistent approach and code of practice across the nation(Department of Transport, 2013). Within this document bridges are identified as critical highways infrastructure since their failure would result in significant impact to the local and potentially national economy. Bridge Management Systems (BMS) have been in place for over 30 years, the systems are used for the planning and development of bridge maintenance routines across various road networks. Initially BMS were developed as a simple data storage tool to collate information such as bridge location and road category, construction and material type and construction date. BMS then progressed to include inspection details and maintenance works and eventually were utilised for future maintenance planning (Flaig and Lark, 2000). There is no single standardised protocol for the establishment of a BMS but they typically include single objective optimisation analysis. In most cases BMS do not take account of performance aspects relating to economy, society, environment or even network wide impacts. For this reason, in many cases current BMS are no longer fit for purpose and require a system with can accommodate multiple performance goals based on various weighted performance indicators. As our world becomes more connected the interdependency of infrastructure systems increases, since these systems have often grown from small local needs they were not deigned to function as the national global networks they have evolved into today.

To transform the current management structures a national digital approach must be implemented. In line with the this the UK government has committed to a digital strategy to transform infrastructure performance. This long-term programme is aimed at improving the delivery and performance of infrastructure by changing the way infrastructure is planned, procured, delivered and operated(Authority, 2017). In future, the way infrastructure is planned and delivered will transform due to the impact of digitization, changes in technology and growth of city regions. Existing best practices and systemic issues that limits the UK's infrastructure performance are currently being investigated to understand how digital technologies and innovations can tackle the issues thus implementing an Industrial strategy. This productivity programme moves beyond the economic efficiency of individual project in a system and focuses on whole life performance of systems (Authority, 2017). Value for money, user satisfaction and benefits to society can be ensured only if the opportunities throughout the life cycle (both construction and operational phase) of the asset is utilized to enhance the performance rather than focusing only on the capital efficiency of the project which is just a component of delivering whole life value and high performance. The HIAM has been implemented in various degrees across regional areas of the UK resulting in the publication of ambitious action plans by individual county councils (Furuta, Frangopol and Akiyama, 2014). However, such plans focus on the overall management of Highway infrastructure rather than a strategic, tactical and socio-technical approach to bridge management (van Dam, 2009).

Within the highway infrastructure bridge decks form approximately 2% of the linear asset but account for ~30% of the total asset value. It has been estimated that the maintenance cost per km of bridges or tunnels is 10 fold that of road km (Crispino, 2017). Hence the effective management of structures maintenance planning has the largest potential to impact the future sustainability of our road networks. In recent years there has been a rapid deterioration in the condition of bridges in the UK. In one year 2017-2018 the cost of bridge maintenance backlog increased by 34% to £6.7bn to address this the next decade will see the largest ever investment in the UK strategic road network as part of the £600bn infrastructure pipeline. In the past BMS were designed as independent systems, this has led to siloed investment planning. There is an urgent need for a BMS must be designed to form part of an ecosystem of infrastructure systems ultimately leading to a national digital twin.

A Digital twin is a system level model or digital model of physical things that can be used for planning and simulations which can help in increasing the efficiency and resilience. It enables better use, planning, delivery, maintenance and operation of assets, systems and services (Bolton A, 2018). With the assistance of predictive analytics, big data and machine learning approaches, UK can develop digital twin for its infrastructure which enables performance optimisation, support planning decisions and powers predictive asset maintenance and demonstrate global leadership in digital twin technology (National Infrastructure Commission, 2017) Creation of National Digital Twin (NDT) by connecting digital twins forming an ecosystem of digital twins by securely sharing data will unlock extra value (Bolton A, 2018)

Pressure on infrastructure has been risen tremendously due to climatic change, economic growth and increasing population. There is a need for an optimised system to reduce the disruption and congestion in the UK's existing infrastructure. The National Infrastructure Commission (NIC) has its focus on how these technologies can be utilised to better understand the existing infrastructure and increase the productivity in a collaborative way(National Infrastructure Commission, 2017). To transform the infrastructure smarter, artificial intelligence, sensors, cloud computing and machine learning can be used and managed. This indeed requires more information which in turn helps to gain better understanding about the nation's infrastructure.

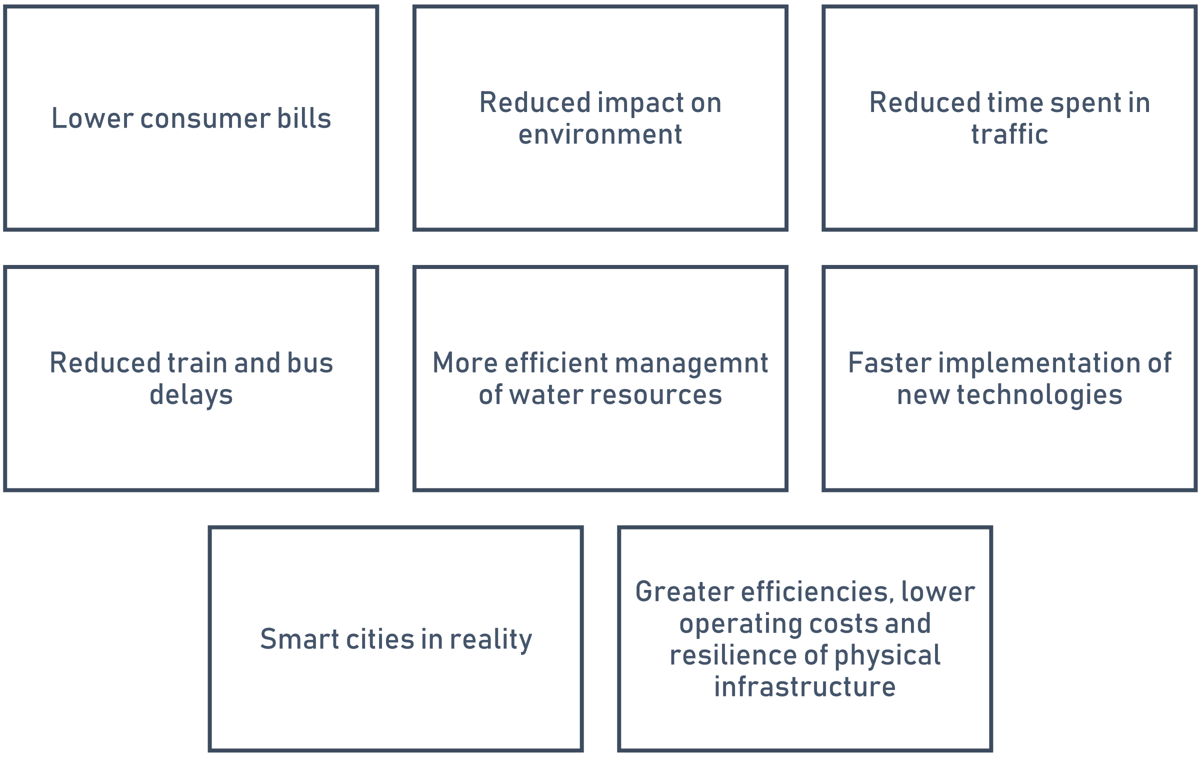


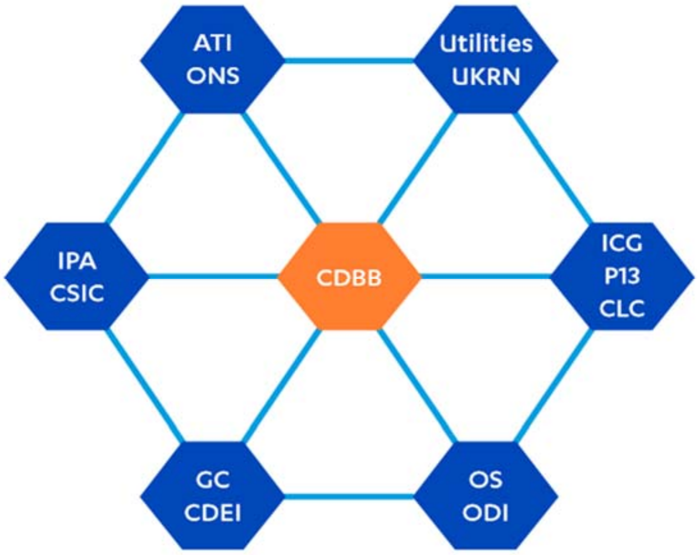
Figure 1 Accruable Benefits from having and sharing better data

Data is vital to improve the way in which the infrastructure is optimised throughout the life cycle of the asset and the system as a whole. High quality data should be collected and used effectively to improve nation's infrastructure. Significant economic benefits can be provided by data. With appropriate security and privacy arrangements, sharing data can catalyse improved services and innovation (National Infrastructure Commission, 2017).

UK is in need for digital framework for sharing data and digital twin pilot project which provides opportunity to transform data about infrastructure to shared interoperable format thus increasing the resilience, performance and efficiency of the nation's infrastructure. So, the Commission made recommendations to task the relevant organisations for establishment of a digital framework for infrastructure data and pioneering digital twin models

Digital framework

Better understanding of interdependencies between infrastructure sectors and assistance to break down silos will be enabled by a digital framework. This framework with common standards of interoperability for sharing the infrastructure data will help infrastructure sectors to coordinate. The recommendations are made by the Commission with full acknowledgement of complexity of delivery. Coordination of key players in the framework in sharing infrastructure data is complex and is a challenge. It also requires willingness of the key players to collaborate through a new cross-sector approach shown in Figure 2.



Institutions integral to the digital framework (as an evolving list)	
Centre for Digital-Built Britain (CDBB)	Utilities and network operators
Cambridge Centre for Smart Infrastructure and Construction (CSIC)	Regulators
Infrastructure Client Group (ICG)	Open Data Institute (ODI)
Project 13	Office for National Statistics (ONS)
Infrastructure Projects Authority (IPA)	Ordnance Survey (OS)
Construction Leadership Council (CLC)	Geospatial Commission (GC)
Alan Turing Institute (ATI)	Centre for Data Ethics and Innovation (CDEI)

Figure 2 Digital Framework (National Infrastructure Commission, 2017)

The Gemini Principles

Centre for Digital Built Britain proposed set of principles to guide for enabling the national digital twin and the information management framework which are called as Gemini Principles (Bolton A, 2018). Acknowledgement of the potential gain while removing the hinderances in sharing the data due to cultural, technological and commercial barriers revealed the ad hoc development and embrace the use of the coordinated information management framework and a national digital twin.

Digital twin as mentioned earlier is a digital representation of physical reality of assets at a level of accuracy suitable for its purpose. A Number of digital twins are already developed for range of purposes and few are connected to share data across sectors, organisations or geographies. The key constraint is lack of interoperability.

The NDT ambition is for an ecosystem of numerous federations of digital twins but will never be connected to every other digital twin or become fully federated because there would be limited value in doing so. On the other hand, there is no end for the built environment so even connecting all digital twins can never be completed. NDT establishes the approach of secure interoperability which is its inception and not its completion. This interoperability offers great value locally and nationally to the public and private sectors. Therefore, it is the national approach to manage information within the ecosystem of digital twins. The development of the information management framework and the NDT will be guided by the Gemini principles which are organised under three comprehensive headings: purpose, trust and function as shown in the figure below.

Figure 3 The Gemini Principles

Proposed Bridge Management Decision Support Tool

The Northern Ireland (NI) Department for Infrastructure (DfI) are responsible for the management and operation of all key infrastructure assets in NI including; maintenance of road networks, road safety and vehicle regulation policy, rivers and sea defence, communications systems and regional strategic planning and development. In comparison to the rest of the UK and Ireland, NI is unique in that the entire transport network is effectively owned and maintained by DfI, therefore it provides the only opportunity to develop a fully holistic network wide digital overlay to take account of the interdependency of assets. This places NI in a strong position to develop a pilot study to demonstrate the potential of a national digital twin. The current structural maintenance backlog on the NI road network sits at £1.2billion highlighting the need for a shift from the current reactive based maintenance methods. DfI in collaboration with Queens University have commissioned the development of a new BMS for the management of over 6000 bridges across the Northern Ireland Road Network (NIRN) (Figure 4). A key aspect of the new BMS is that it will form the basis of a central data hub or digital twin for all NI infrastructure. The system will act as a demonstrator and the concepts will be transferrable across all elements of infrastructure in NI leading to a fully interoperable infrastructure management system for the region which will take account of the NDT framework and The Gemini Princilpes.

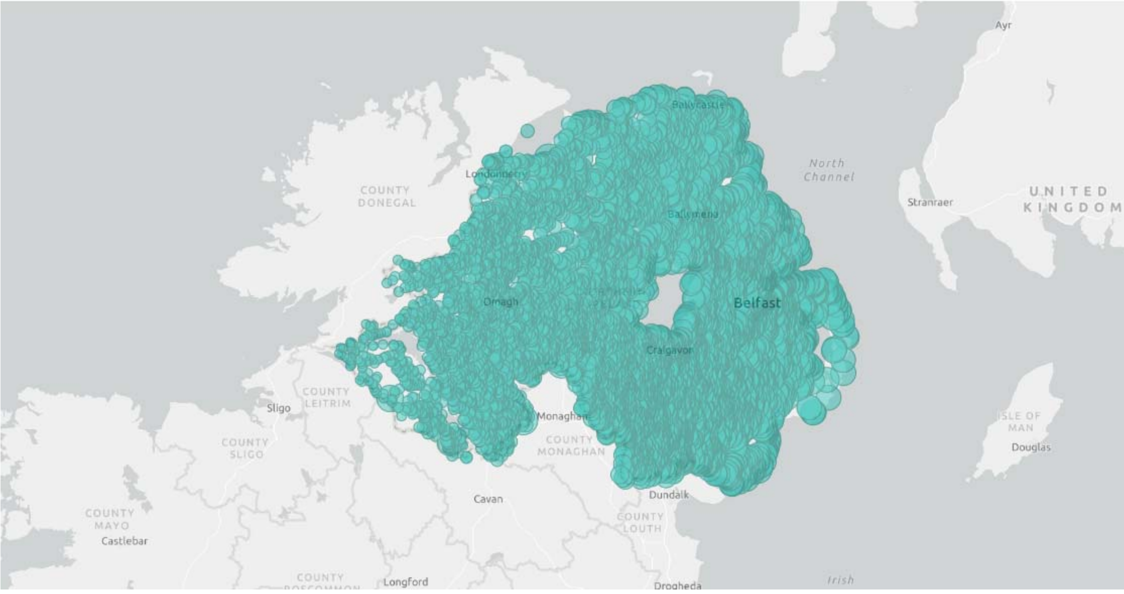


Figure 4 Locations of bridges within the NIRN

The proposed bridge management decision support tool (BMDST) will replace the existing BMS with an ultimate goal of transforming the current approach to asset management within our transportation networks. The methodology will aim to address the recommendations of recent infrastructure reports focused on increasing the resilience and reliability of our road network(McKibbin, 2016; Yatteau and Professor Lord Mair, 2016) Data analytics, machine learning, clustering, deterministic and probabilistic predictive tools will enable a transformation from reactive to predictive maintenance of our critical structures. The potential for the analysis of data from isolated bridge management systems has previously been demonstrated(Dromey *et al.*, 2016). The system will be developed through three interdependent work packages detailed in this section and will be fully operational by 2022.

Figure 1 Conceptual image of BMDST

Work package (WP) 1: Enabling predictive maintenance.

This WP will develop and shape the way in which data on road infrastructure is collected and shared to provide a step change from reactive maintenance to predictive maintenance of structural assets within the network. Existing historical data on bridge repairs and deterioration will be explored to identify and isolate the significant factors which influence degradation of structures. A feasibility study to determine most suitable platform for BMDST will facilitate the development of an architecture to integrate information from the existing BMS with regional information such as traffic, river properties and relationships with flood events, soil and climate, This involves establishing a framework which would facilitate a fully interoperable technology platform to allow for network wide performance analysis. Mathematical methodologies will be developed to identify relationships and correlations between structural condition, material properties, climate and traffic using an AI approach. This holistic approach will allow for determination of Key Performance Indicators (KPIs) for the future monitoring of structures while also providing an indication of the vulnerability of the network to climate change. The structured data set will then be analysed to identify suitable deterministic and probabilistic predictive tools for accurate forecasting of future maintenance program.

WP2: Risk consequence mapping.

WP1 will enable a transformation to predictive maintenance for our road network. This WP will establish the methodology for determining suitable multi-criteria vector within decision making tool, forming a connection between structural condition, service importance and societal impact. This socio-technical system will be formed with the same physical assets of the existing BMS but the decision making will be supported by a social and economic system Regional information on population density and socio-economic groupings, emergency service resources will be used to determine service importance of structure(Zaharah *et al.*, 2018). This will lay the foundation of a risk consequence map across network to understand the practical consequences of road closures, extended repair programs or failure. Most importantly this will consider interdependency of assets within the network and the cascading effects due to service loss but with guidance on the consequences of over/under prioritising certain factors and final aggregation(Shimray, Singh and Mehta, 2017). This will not only allow prediction of future behaviour but will also allow for greater understanding of the dynamics of the whole system and sub systems as proposed by the national digital twin framework.

WP3: SHM and integration of future technologies. The cost of repairing damage in large structures increases rapidly as the damage approaches criticality. However, without monitoring, the prediction of deterioration and hence early intervention is extremely difficult. Therefore, the integration of accurate monitoring data from SHM technologies is critical in establishing the proposed BMDST for smart management of bridges within our road network. It is the monitoring techniques established within this research that will enable data from the past to be exploited for systems for the future. In order to reduce dependency on the current labour-intensive visual inspection methods SHM systems will be integrated to the proposed BMDST. SHM systems will be installed on bridge sites which are representative of identified bridge clusters. The monitoring data will be collected based on established KPIs and suitable remote data collection will be established. The fundamental aspect of this research is the input and use of SHM data to inform a decision-making framework. The greatest limitation of SHM data is the lack of historical data, in order to make our bridge inspections more efficient, economical and effective at a local and global level we need to establish baseline data sets (Catbas, Moon and Aktan, 2010). The SHM data collected will provide information which will be synchronised with BMDST to allow for live automatic updates on bridge condition. Vision based SHM shows the greatest potential for portable cost-effective monitoring of our infrastructure both at a structural condition and traffic assessment (Lydon *et al.*, 2019)Interoperability across data sets forms the core of this research and provides the greatest opportunity with minimum cost. Hence, a critical element of this research is the integration of existing CCTV systems for validation of traffic model and future collection of traffic data. The incorporate such crowd sourced data for routine inspection would have significant economic effect on maintenance costs.

Discussions & Conclusions

In recent years there has been significant investment in the development of digital strategies for improvement in the delivery operation and maintenance of UK infrastructure. To date there has been no clear case study to demonstrate the complications, limitation and benefits of the establishment of a National Digital Twin. The digital Twin Task Group is now forming the foundation of how this might be realised across the UK. This paper has presented a proposed BMDST which will be designed to meet the recommendation of the National Digital Twin Framework and hence act as a demonstrator the rest of the UK. Highlighting the benefits of a single holistic management approach for both strategic and national road networks to allow for the interdependencies of the entire road network to be understood.

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