Developing a common framework for a Bridge Management System at national level

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ABSTRACT: Transport infrastructure is directly impacted by climate change as extreme weather conditions account for 10-35% of delays/service interruptions to road and rail infrastructure. The current reactive method of maintaining bridges within these infrastructure systems results in a lack of contingency capacity and ultimately a reduced ability to adapt to uncertain future needs. To allow infrastructure providers to prepare for future events, there is a need to develop asset management systems (AMS) with embedded decision-making support which considers factors such as climate change and population growth. A National approach would enable strategic risk assessment to mitigate the consequences of climate change and enhance resilience across aging infrastructure. This paper aims to establish a common framework for the collection and management of highway bridge data incorporating interoperability across other AMS systems to enable better strategic decision making and fact-based investment optimisation. Common features are identified to enable data linkages across multiple systems which will ultimately facilitate the development of an architecture for a GIS based bridge management system with integrated micro-services systems. The research is based on the current and historic data held by the Northern Ireland Department for Infrastructure, who are currently responsible for the management of all roads and rivers in the region.

KEY WORDS:; Bridge Management; Infrastructure Lifecycle.

1 NORTHERN IRELAND ROAD NETWORK

Currently the Department for Infrastructure (DfI) Northern Ireland (NI), is in a unique position within the UK, in that, it is responsible for the strategic unified management and delivery of key infrastructure systems including transport, flood defences and rivers in NI. This provides the opportunity to, for the first time, establish a true link for interoperable infrastructure systems to make better, more informed decisions. This paper focuses on the development of a common framework for national bridge management systems (BMS) which would enable a strategic assessment of vulnerability of ageing structures across transport networks. The framework has been developed using the NI road network as a demonstrator, the proposed system will replace the existing BMS in NI which is no longer fit for purpose. The current BMS holds 20 years of inspections in an independent Sequential Query Language (SQL) database which does not easily link with other data sources across the department such as rivers or the bridge maintenance and repair work. The current BMS holds bridge location data using the Irish Ordnance Survey National Grid coordinates. Therefore, bridge locations from across the region can be mapped although the current system does not connect any detailed bridge properties or inspection details to the map.

Inspections are carried out on the standard schedule of every 2 years for a general inspection and 6 years for a principle inspection. Defects are recorded against each element and are scored according to Bridge Condition Index (BCI) and a maintenance plan is created if necessary. This maintenance and repair work is held in a separate system (Works Orders) and there is no link between the 2 systems. The repair work is carried out either as a group, for small repairs, or singly, for large repairs. This repair work is then recorded against the awarded contract, and the contractor rated on efficiency and quality (in a separate system).

The ability to link the BMS and Works Orders systems together would allow for a greater understanding of how defects being repaired relates to the full lifecycle for each bridge[1]. The joining of the two systems would also give added benefits such as costings for the maintenance of each bridge as well as allowing the analysis of historical data to determine which bridges are expensive to maintain and which may be worth replacing. There are also potentially hidden benefits and risks to linking these systems that may not be discovered until they are actually linked.

2 FUTURE PROOFING

Transport infrastructure is directly impacted by climate change as extreme weather conditions account for 10-35% of delays/service interruptions to road and rail infrastructure. During 2009-2014 severe flooding resulted in a large number of road bridge collapses in the UK, most notability events in Cumbria in 2009 which resulted in loss of life and an estimated £279million economic cost [2]. Currently 10% of major road assets in the UK are located in areas with significant chance of flooding but this has been predicted to increase to 50% by
The current reactive method of maintaining bridges within these infrastructure systems results in a lack of contingency capacity and ultimately a reduced ability to adapt to uncertain future needs. To allow infrastructure providers to prepare for future events, there is a need to develop asset management systems (AMS) with embedded decision making support which considers factors such as climate change and population growth. A national approach would enable strategic risk assessment to mitigate the consequences of climate change and enhance resilience across aging infrastructure. Increased urbanisation and limited river improvements has led to rivers receiving more water runoff, at a quicker rate than in the past. This results in high fluctuations in river flow ultimately leading to more regular and severe flooding. The climatic changes from global warming also adds to this problem as we have high intensity short duration storms that cause flash floods. The current method, developed for NI, of predicting flows is based on a statistical approach utilising limited pooling stations data which is often inaccurate and invalidated. The interaction of urbanised drainage infrastructure with transportation infrastructure can result in vulnerabilities at bridge locations. The above issues can cause increased flow and depths at many bridge sites that can result in pressurized flow that enhances scour and causes failure of the bridge. Therefore, understanding the interaction of hydraulic and structural behaviours will be critical in ensuring the safety of bridges across all road networks. The broad umbrella of responsibility of DfI provides a unique opportunity to connect existing datasets from rivers with BMS data. DfI was formed in 2016 through the amalgamation of Transport NI, The Rivers Agency and Department of the Environment as a result the separate existing AMS remain separate within the organisation. The paper details the system architecture for a GIS based BMS which will enable connectivity across the systems to facilitate a greater understanding of the maintenance requirements of the network. One example would include the identification of structures which are vulnerable to flood events or tidal surges and allow the department to take appropriate, proactive action to mitigate the risks.

3 PROPOSED SYSTEM ARCHITECTURE

Along with predictive maintenance and life cycle analysis the proposed BMS must be capable of spatial analysis to measure the impact of changing climate and urbanisation. This will enable strategic management of transport networks which will ensure future resilience and secure connectivity.

The proposed elements of a unified BMS are presented in this section. Fig. 1 shows the proposed lifecycle of a bridge and how this could be linked to associated systems, such as sensors and rivers, to produce a full picture of how environmental conditions could have an effect on a bridge and its maintenance cycle.

![Figure 1 Lifecycle of a Bridge (and associated systems)](image)

3.1 Bridge inventory and condition

Information held within the Bridge system will include:

- General bridge information including geometric and material properties as well as geographic positional data.
- Inspections and Maintenance information including historical inspections, defect photos and completed maintenance records.
- Reports and spatial mapping including statistics on inspections, bridge condition and mapping facilities to enable visualisation of bridge groupings based on various user selected parameters.

Currently all bridges require a visual inspection. This involves a physical visit to the bridge and visually inspecting all the various components of that bridge to assess condition. Visual inspections are subjective in nature. However, immediate remote access the bridge history during each inspection would enable better judgment of deterioration in condition by the assessor. This will be enabled though a mobile element of the system architecture.

This element will have embedded GIS capability to allow inspectors to spatially plan multiple inspections. Enabling a more efficient clustered inspection programme which will inform on grouped maintenance planning.

The proposed system must allow for the incorporation of future technological advances such as computer vision and machine learning. Challenges relating to surface damage of structures can now be accurately measured by vision based methods[5]–[7]. Computer vision involves analysing images to determine changing properties of their content. Digital image correlation (DIC) was first proposed by Chu [8] and is now increasing in popularity across science and engineering disciplines. With dramatic improvements in commercially available digital cameras it is becoming a versatile and cost-effective analysis method. The ability to record defects while inspecting will facilitate digital analysis of the defect images to provide accurate quantification of the deterioration.

Whilst having the requirements above would enhance any bridge management system, finding a way to incorporate them...
into a mobile device could prove costly and, therefore, prohibitive. A solution would be to use GI tools, such as ESRI’s survey123 [9] to record the inspection. This software can be installed on a smartphone or tablet via a mobile commerce application and solves many of the issues above. There may be difficulties to overcome using a 3rd party tool, such as linking with a bespoke system and network connectivity issues, but should these be addressed, the ability to inspect without cumbersome laptops or paper files, would prove beneficial.

3.2 Maintenance history and effect of maintenance

Currently, there are no connections between the existing bridge management system and the maintenance and works system within DfI. These are both treated as standalone systems with no straightforward means of linking them together. Initial work has been undertaken to develop a common link across the systems, which involves a manual process of searching the notes and comments for bridge references and using those to search the BMS. Work history is manually inputted into the current BMS but has often not been undertaken which means an accurate work history on that structure is missing. This is very time consuming and requires an in-depth knowledge of both systems. It is also inaccurate and dependant on the notes field containing a bridge reference, which many do not possess. The current maintenance system covers all maintenance and works carried out on infrastructure such as roads, bridges and other structures. Including work such as patching of potholes, surface dressing or repair work to a bridge structure. This work is either grouped into packages/schemes which encompass several roads/bridges or alternatively individual work packages for a single road/bridge whichever make better fiscal sense. Recorded work packages include details such as vegetation clearance or minor works, with individual works including activities such as severe or major structural work which requires a longer program of work and on site supervisory staff.

The works order is issued to either an external Term Contractor or assigned to an internal department Operational and Maintenance direct labour workforce depending on the nature and complexity of the job in hand and geographical location. On completion, this work is inspected and approved or remedial works instructed prior to payment. Following the completion of the scheme, the contractor’s performance is assessed on Key Performance Indicators, which could have an impact on future contract competitions.

3.3 Quality management system

Quality Management System (QMS) is a set of engineering standards and processes used to improve the performance and consistency of any approach. These processes are currently held separately and used by certain applicable sections of DfI. They are often not considered when developing a bridge maintenance system as they are only guidelines. Including a QMS in any bridge maintenance system will improve the quality of that system as well as ensuring that standard approaches by all users of the system are adhered to. In order to comply with BS EN ISO 9001:2015, DfI Roads implemented a compliant QMS procedure which needs to be followed. Schemes and sections are regularly audited both by internal auditors and external auditors to ensure compliance. The QMS covers a wide range of activities and processes such as shared procedures for record control, equipment registers and correspondence. Project delivery such as resurfacing, minor works and term works, structural inspections, laboratory tests. Site operations including pre-site, supervision, completion and payments. Including, at the very least, some of the above functions will lead to an improved service and a streamlined approach to the entire process of maintaining infrastructure.

3.4 Flood predictions and damage functions

DfI Rivers have developed extensive flood prediction data which planning authorities use for flood damage prediction to buildings in future events. Several models have been created using both historical records, photographs, drawings and statistics to create the historical flooding map and broad scale flood mapping of NI. This can then be used to target, at risk, rivers and coastlines. Using this information in the context of bridge damage will help demonstrate a societal and economic impact of the loss of specific bridges. All flood data is provided as open data by rivers and is easily accessible via their website [10] This data is updated annually with a new flood model provided based on year. This allows for historical searches as well as an opportunity to keep the citizen well informed.

![Figure 2 Example of flood prediction (Dromore, NI)](image)

Rivers throughout NI have been mapped using Geographical Information Systems (GIS) modelling software to produce 2D maps. These maps include river channels as well as culverts, weirs and flood defences. Models such as the Digital Terrain Model (DTM) have been created using Light Detection and Ranging Radar (LIDAR) to provide ground height data, while the hydrology model is based on the Floods estimation Handbook[11] (FEH). The FEH also has a web service to complement its handbook methods. Models are run for probability (high, medium, low). The maps produced take into account flood defences and the extent shown is the maximum extent possible over the duration of the model. All the Rivers models are sensitivity tested and validated against historical data (where available). Figure 2 shows the varying severity of a flooding scenario, from light blue (low) to dark blue (high). Hydrometric stations are located at strategic locations across the whole of NI on each river (Fig. 3). Historical data has been collected by Rivers Agency since 1971. This comes in the form of Ariel photography and archived field data. This data only covers areas that have been previously flooded.

Using data from the Rivers models would enable a fuller environmental picture to be created and facilitate the identification of network fragilities at bridge locations, should they fall into one of the flood zones created in the models. These models, combined with historical data on bridge
inspections, can then inform an early warning system that alerts the bridge owners of potential issues, such as scour, earlier than the prescribed inspection period thus allowing for key responsive decisions to be made in advance.

Figure 3 Map showing Hydrometric stations and their location

3.5 Environmental conditions

In recent years, scour has been identified as the underlying cause for the majority of bridge failures in the UK and Ireland, including the Malahide rail bridge collapse and those witnessed in Cumbria in 2009 [2], [12], [13]. Rapidly changing river properties including, flow depth and turbidity has been shown to have an impact on bridge deterioration. DfI Rivers agency have information relating to river properties held via gauging stations positioned throughout NI (Fig. 4). These stations provide upstream and downstream flow data. This research will detail the requirements for this information to inform the BMS and increase the accuracy of predicted bridge deterioration.

Figure 4 Gauging station map of NI

3.6 Design

A system that pulls together the elements explored within this paper will allow for a more detailed picture of the bridge and its complete lifecycle from construction to decommissioning and replacement. The amalgamation of the current bridge system (SMS-r) and the maintenance system (Works Orders) will allow for better decision making (Fig. 5). This involves establishing a framework which would facilitate a fully interoperable technology platform to allow for network wide performance analysis.

The connection of these systems requires a common attribute. This attribute should be unique to each piece of infrastructure in the system. This unique property will allow the structures data to be connected to the maintenance system (Works Orders) data and allow the collection and collation of data via the QMS aspect to ensure all audit requirements are covered.

A key objective of this research is to establish a system which is fully interoperable with existing and future rivers data to highlight areas at risk as well as potential bridges that could be damaged and require inspection.

Figure 5 Amalgamation of 3 current systems into 1

The map in Fig 7 shows the potential use of this data, by showing users which bridges are near gauging stations to identify locations whereby the river flow data and bridge condition data can be analysed to determine a correlation between hydraulic and structural properties.

Figure 6 Map showing masonry arch bridges & gauging stations.

The map in Fig 7 shows the potential use of this data, by showing users which bridges are near gauging stations to identify locations whereby the river flow data and bridge condition data can be analysed to determine a correlation between hydraulic and structural properties.
Green triangle shows bridges susceptible to scour, red stars are bridges, with blue circle donating a selected bridge near gauging station (green circle). Red circle shows further bridges upstream susceptible to scour, while blue arrow donates river flow. This information will enable an inspector to target a set of bridges all with related defects.

Work is now underway to develop a consistent system that incorporates full lifecycle management and ensures that the standard assessment of bridges across the network.

The cascading effects of inadequate infrastructure has rippling consequences on societal wellbeing with measured increases in unemployment rates in areas with a lack of connectivity and long term underinvestment[14]. The absence of fact-based assessment across critical infrastructure compromises economic vitality, future resilience to climate change and enables the continuation of social divisions and investment which is often based on a political legacy. A shift to a data-driven decision-making model would enable fact-based investment and unlock value and social equality and ensure national mobility. Assessing the impact that a loss of a bridge has on society can be difficult. Finding a way to highlight this loss, would benefit the system and allow better decision to be made. Measured social impacts include[15]

- Community isolation
- Loss of business
- Lack of public transport
- Economic impact

These risks are not currently considered when assessing a bridge and with an increased possibility of flooding and extreme weather due to global warming this increases uncertainly about the future sustainability of ageing critical infrastructure. A recent study by Stanford University in the USA has highlighted this lack of consideration as a large risk [16] and any system that considers this impact must be a more sustainable approach.

4 CONCLUSIONS AND FUTURE WORK

The result of having all of the above data linked together, will be an enhanced decision making and maintenance assessment tool. Having early warnings when bridges are at risk as well as considering factors such as societal impact will benefit infrastructure managers. Setting bespoke maintenance plans for each bridge automatically, will achieve the aim of maintaining more bridges with less resources, while targeting specific, at risk, bridges with embedded sensors will minimise the potential for preventable severe damage/destruction of a bridge thorough early intervention.

Currently, not all bridges in NI and the UK are assessed under comparable criteria. DfI use BCI while 3rd party organisations like Amey and Intertoll use the older legacy inspection criteria of an overall priority. The 3rd party inspection data is reported to DfI on an annual basis and manually input to the central SMSR. The proposed system will facilitate audited access for 3rd party organisation to directly input inspection data as it is collected on site. The inspection cycle is standardised, and no special circumstances are considered unless identified by an inspector. An added benefit to have all the data linked together via 1 system is that detailed analyses can be carried out on each bridge. This allows each bridge to be assessed individually based on its own unique set of circumstances.

Having this data collected together in one dataset allows the production of GIS layers. These layers can graphically show bridges and other assets on a map. The map can then be filtered, based on pre-determined criteria to allow analysis. An added benefit of having map-based data would be the introduction of mobile inspections, where all the data is available to the inspector on site. Having the ability to link several systems together with one unique identifier allows existing systems to be targeted. Additional functionality developed via new systems, not yet developed need to be considered also.

With this in mind, the system should be designed to be flexible enough to incorporate new additions and new ways of monitoring. The micro service approach to the system design should allow for the addition of future services, such as SHM, LIDAR scans and further infrastructure such as Vehicle Restraint Systems (VRS) and masts. These and other features should be added easily, if judged beneficial to the current system.

Work is now underway to develop a consistent system that incorporates full lifecycle management and ensures that the
system is not being built in isolation, a survey of current bridge management system owners will be completed.

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