Institution: Queen's University Belfast		
Unit of Assessment: 10		
Title of case study: A data analytics driven smart alerting system for Structural Health Monitoring		
Period when the underpinning research was undertaken: 2005-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting**
Adele Marshall	**Reader Professor of Statistics**	**2001 - present**
Su Taylor	**Professor in Structural Engineering**	**2003 - present**
Myra Lydon	**Royal Academy of Eng. Research Fellow**	**2018 - present**
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

The timing of 'replace, repair or extend service' decisions for infrastructure is a significant challenge for local authorities. To address this, researchers at Queen's University Belfast (QUB) have developed a cutting-edge Structural Health Monitoring (SHM) smart alerting system to monitor structures in real time to directly inform decision making at local government level. By embedding data analytics models within an intelligent diagnostic framework, this unique system has delivered step-like improvements in infrastructure monitoring in Northern Ireland (NI). To date, it has resulted in 'extension of service' for assets with a replacement cost > GBP40,000,000 within the critically underfunded budget of the Department for Infrastructure. SHM has also demonstrably transformed 'risk to life' assessment and practice in NI.

2. Underpinning research (indicative maximum 500 words)

All load-bearing structures deteriorate over time. While construction standards can ensure integrity over the short to medium term, on longer timeframes this will become increasingly dependent on the nature of strain applied (*i.e.* frequency, magnitude and type of load). To date, monitoring of this deterioration has broadly been conducted in a reactive mode on a structure-by-structure basis with only limited data being recorded (*i.e.* visual inspection) **[R1]**.

Prof. Adele Marshall, working in the Mathematical Sciences Research Centre (MSRC) at Queen's University Belfast (QUB), has focused heavily over the last decade on implementing cutting-edge data analytics at the front end of statistical models to increase their overall efficiency and efficacy. Prof. Su Taylor and Dr Myra Lydon from the School of Natural and Built Environment (QUB) developed the real-time, high capture rate diagnostics to feed real world data into the new suite of models.

Structural Health Monitoring (SHM) seeks to dramatically improve on this approach by interrogating, in real time, the large data sets provided by remote diagnostics. A data analytics driven front end underpins a smart system that diagnoses the progression of 'true' deterioration in structures by rejecting 'false' alerts. SHM reveals if assets must be replaced, repaired or, crucially, if their service life can be extended (resulting in significant cost savings).

Researchers in QUB have developed a novel data analytics-led approach to tackle this issue:

'Health' modelling [R1, R2, R3]: By developing scalable analytic models, large volumes of data are harnessed to provide new statistical insight into how structural health assessment can be transformed to provide new sets of Key Performance Indicators. In addition, a new approach to statistical process control provides a smart sampling capability for collected data.

Monitoring [R1, R4, R5]: Developing a diagnostic network to allow data collection in a robust and effective manner that can be assessed within the framework of the above health modelling.

<u>'Health' modelling for built environment:</u>

Coxian phase-type distributions: Estimating 'length of stay' in stages of deterioration.

The breakthrough approach to determining the progression of deterioration in SHM is the novel application of statistical modelling which, as outlined in by the Head of Highway Maintenance DfI in **[S1]**, *"previously applied to patient health maps equally well to bridge health where the phases in the Coxian represent the stages in bridge survival as states in a Markov model"* **[R1, R2]**. This work was originally performed to understand why delays emerge during a patient's stay in hospital *i.e.* assessment, treatment, discharge *etc.* Generalising, the *Coxian phase-type distribution* (a special type of Markov model) allows categorising length of stay (patient survival) into particular phases, or stages, and identifying key characteristics (covariates) related to such stages of patient survival. For SHM, this modelling allows the identification of key indicators that underpin bridge survival within large data sets **[R1]**.

Defect Mapping P-charts (DM-P): Visualising true/false alerts requiring intervention.

While mining large data sets allows Key Performance Indicators to be extracted, it is essential that the data being analysed is a true representation of events linked to deterioration. Developed by MSRC in QUB, DM-P is a performance evaluation metric intended for the analysis of real-time smart alerting systems to inform decision making **[R3]**. DM-P was originally developed to handle large volumes of data in real time to inform life-saving clinical decision making. However, as highlighted in **[S1]**, this has *"directly resulted in collaborative development of SHM systems"* by providing the crucial link between data acquisition and modelling. This can be clarified as follows: to integrate the data from the remote devices in **[R4, R5]** with the modelling in **[R1, R2],** it requires data cleansing and validation (*i.e.* ensuring that the data being used is a genuine alert and removing all false alerts). This is performed in the cloud using the DM-P approach described in **[R3]**. This has meant that interoperability for the core Markov modelling deployed in **[R1, R2]** and data from the diagnostics deployed in **[R4, R5]** are possible, thus permitting the step-like advances in performance provided by smart SHM.

<u>Diagnostic suite for real time monitoring of condition:</u>

To provide the data essential for effective SHM implementation, researchers in the QUB Intelligent Infrastructure Group (IIG) have developed a suite of diagnostics for bridge systems including indirect monitoring using drive-by techniques focused on low-cost technologies such as smartphone global navigation satellite systems (GNSS) and acceleration data **[R5]** and a durable vicinity vision-based system for displacement measurement **[R4]**. This has led to the implementation of SHM smart alert systems on high profile infrastructures such as The Peace bridge in Derry City, The Titanic Dry Dock in Belfast, and the Thames Tideway's Tunnel (see **[S1]** for evidence detailing each project).

<u>Data analytics-led monitoring</u>: Once processed using DM-P, the remote diagnostic data are fed into models to predict how bridge condition will evolve into the future. The Cox Proportional hazards model is enhanced using survival analysis, artificial intelligence and data mining techniques **[R1]**. Overall, this allows accurate modelling for the 'time to an event' along with the identification of underpinning covariates. Here a covariate can be understood as characteristic of a structure (*i.e.* if the bridge is a masonry arch construction type) that may influence the outcome for 'length of stay' in a condition state. This approach has revealed the effect of covariates on the time in different condition states (phases in the Coxian) for bridges across Northern Ireland **[R1]**. The Kaplan–Meier (K-M) survival curves (a method for interrogating stratified data) showed that the time spent in a particular condition state is strongly dependent on covariate and that long-term performance can stabilise in later condition states, again depending on the associated covariate. Overall, this modelling provides the Key Performance Indicators for different structure types that allows long-term projections about condition to be made.

3. References to the research (indicative maximum of six references)

R1. Stevens, N.-A., **Lydon, M., Marshall, A.H., Taylor**, S (2020). "Identification of Bridge Key Performance Indicators Using Survival Analysis for Future Network-Wide Structural Health Monitoring". *Sensors*, 20, 6894. https://doi.org/10.3390/s20236894

R2. Marshall, A.H., McClean S.I. (2004) "Using Coxian Phase-Type Distributions to Identify Patient Characteristics for Duration of Stay in Hospital", *Health Care Management Science Journal*, 7, pp. 285 – 289. https://doi.org/10.1007/s10729-004-7537-z

R3. Novakovic, A, **Marshall, A.H.** (2020) "Introducing the DM-P approach for analysing the performances of real-time clinical decision support systems". *Knowledge-Based Systems* 198, 105877. https://doi.org/10.1016/j.knosys.2020.105877

R4. Lydon, D., **Lydon, M., Taylor, S.E.,** Del Rincon, J.M., Hester, D. & Brownjohn, J. (2019), "Development and field testing of a vision-based displacement system using a low cost wireless action camera", *Mechanical Systems and Signal Processing*, 121, pp. 343–358. https://doi.org/10.1016/j.ymssp.2018.11.015

R5. McGetrick, P.J., Hester, D. & **Taylor, S.E.** (2017), "Implementation of a drive-by monitoring system for transport infrastructure utilising smartphone technology and GNSS", *Journal of Civil Structural Health Monitoring*, 7, pp. 175–189.

https://doi.org/10.1007/s13349-017-0218-7

4. Details of the impact (indicative maximum 750 words)

While infrastructure in the UK ages, performance demands grow, placing increased pressure on maintenance budgets. For bridges in particular, a backlog of maintenance works, identified by the motoring research organisation the Royal Automobile Club (RAC) Foundation in 2019 using data from 2017-2018, will cost local authorities GBP6,700,000,000. And the warning signs could not be clearer. Dangerous underinvestment has recently resulted in numerous high-profile bridge collapses internationally (*i.e.* Ponte Morandi Bridge collapse, Genoa, Italy 2018, Nanfang'ao bridge collapse, Taiwan 2019). Now, more than ever, it is essential that urgent attention is given to this accelerating problem.

In 2016, to address this 'big data' challenge, MSRC and IIG integrated statistical healthcare models **[R2]** and real-time data analytics algorithms **[R3]** into a cutting-edge suite of structural health diagnostics **[R4, R5]**. This allowed for intelligent management, and targeted mining, of large volumes of data on the condition of infrastructure. The outcome was the provision of '*real-time*' feedback to local authorities **[R1]**. By embedding data analytics modelling in SHM a step-like improvement in infrastructure monitoring was realised within a long-standing collaboration between QUB and Department for Infrastructure (DfI) (>15 years). Ultimately, this advance has driven the implementation of a new alerting system for the whole of Northern Ireland.

***Advanced Bridge Management System (BMS)*:**

Data analytics informed budgeting for local authorities.

The implementation of the SHM smart system has provided information that has directly contradicted traditional assessments of bridge condition. As a direct result, DfI have changed strategy on how they manage their assets with the Head of Highway Structures Unit stating that *"QUB are now leading the development of an advanced bridge management system (BMS)".* **[S1]** The overly conservative estimates of previous approaches have been revised because of the SHM smart system which "*for the first time enabled a connection between our legacy inspection methods and BCI ratings hence providing certainty in the long-term performance of our bridges".***[S1]** This resulted in a reduction in the amount of remedial work required and an extending of the safe operation life span of critical elements within the network, as clarified by DfI *"This research has been critical in allowing the safe extension of service life of assets with a capital value in excess of £40 million".* The ability to extend the service lifetime of these bridges, aside from removing unnecessary repair or replacement costs, also dramatically reduces the impact on the NI economy for which bridge closures are major bottlenecks in cities and towns **[S2]**.

Switch to probabilistic assessment practices and grouping by covariate
As part of the Design, Build, Finance, and Operate 2 (DBFO2) Package, Amey Roads NI (ARNI) are responsible for 125km of the road network in NI. The recent advances in bridge condition assessment provided by the SHM smart alerting system have now underpinned a switch from deterministic assessment to QUB-led probabilistic assessment practices for ARNI. In particular, the ability to "*document higher capacity at critical limit states"* meant that *"in each case unnecessary repairs were avoided and higher load capacities were documented for the considered structures than it was possible to demonstrate via traditional deterministic assessment"* **[S2]**. This step-like change in capability is solely enabled by the smart alerting SHM system as it would be prohibitively costly and time-consuming to extract 'true' alerts from this high volume, high frequency data stream to make accurate estimations of bridge condition.

This ability to group families of bridges together for assessment exemplifies how the central tenet of the underpinning research is driving this impact. Here, key characteristics of bridge condition are applied to different covariates (families of bridges) such that for "*bridges of the same type the assessment could be used to directly inform on the decision making process of various other bridges saving in not only the reduction of remedial action required but also the reduction in the amount of road closures needed to facilitated the works*." **[S2]**.

On-site safety:

Smart alerting to assess 'risk to life' in real time.
At the very core of SHM is human safety and disaster prevention. The QUB smart alerting system has allowed quantum leaps in performance for on-site 'risk to life' assessment and practice in NI.

In 2020, DfI were performing remedial works on a retaining wall at a filling station **[S1]**. As outlined by the Head of Highway Structures Unit these "*works resulted in a partial collapse of the wall so the QUB monitoring system was installed on the remaining sections of the wall to gauge any small changes in condition*." The SHM algorithm "*developed by the MSRC was capable of real time analysis of 3000 data points per second*". The key point here is that smart alerting successfully allowed 'true' movements of the wall to be extracted from background noise and vibrations "*which acted as an early warning to cease works on site*". The impact of this was three-fold: structure preservation, environmental security, and safety of staff, as highlighted directly in **[S1]** "*This prevented further collapse of the wall which would have resulted in catastrophic environmental consequences from the fuel tank and also posed a risk to life for 3 workers in the area immediately behind the wall*." While estimates of cost savings extending to millions could be associated with the first 2 impacts here, (*i.e.* business/road closures and clean up from environmental spills in addition to reinstatement costs), the risk to life benefits can never have a cost estimate associated. This is direct evidence of a core impact for which this system was developed.

Along with informing spending decisions for local authorities and real-time monitoring of safety risk, the impact of the QUB smart SHM system stretches into other aspects of public life as infrastructure under the auspices of DfI is core to the daily function of NI and its people.

***Cultural Impact*:**

Maintaining the structural legacy of NI

The SHM systems have also been utilised on several bridges that not only have an important role in the road network but in some cases have significant cultural values.

One such structure is the *King's Bridge*, built in 1912. Few concrete bridges were built before the First World War, so this is a rare surviving example from this era. The QUB SHM system was deployed on this bridge to undertake a quantitative assessment of bridge condition and returned a result that overturned that of visual inspections. As a result the bridge was "*deemed fit for service*". Prior to the work undertaken by QUB, this listed bridge had been scheduled for decommissioning and replacement which was estimated to cost GBP10,000,000. Overall SHM smart alerting returned an immediate cost saving to DfI, prevented significant disruption by avoiding the closure of a key arterial link in Belfast and allowed the preservation of an important historical element of the history of NI **[S1]**.

Improving public perception:

The Peace Bridge is an iconic bridge in Northern Ireland which costs GBP14,600,000 and was opened in 2011, during periods of heavy pedestrian traffic excessive vibration of the bridge meant that members of the public had concerns about the safety of the bridge. QUB undertook a monitoring scheme to determine the cause of the excessive vibration which included vision-based techniques along with more traditional acceleration measurements **[R4]**. This work had the direct impact of alleviating "*any safety fears that the public may have had regarding the bridge*" **[S1]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Testimonial letter of the Head of Highway Structures Unit, Department for Infrastructure (DfI)

[S2] Testimonial letter from the General Manager, Amey Roads NI