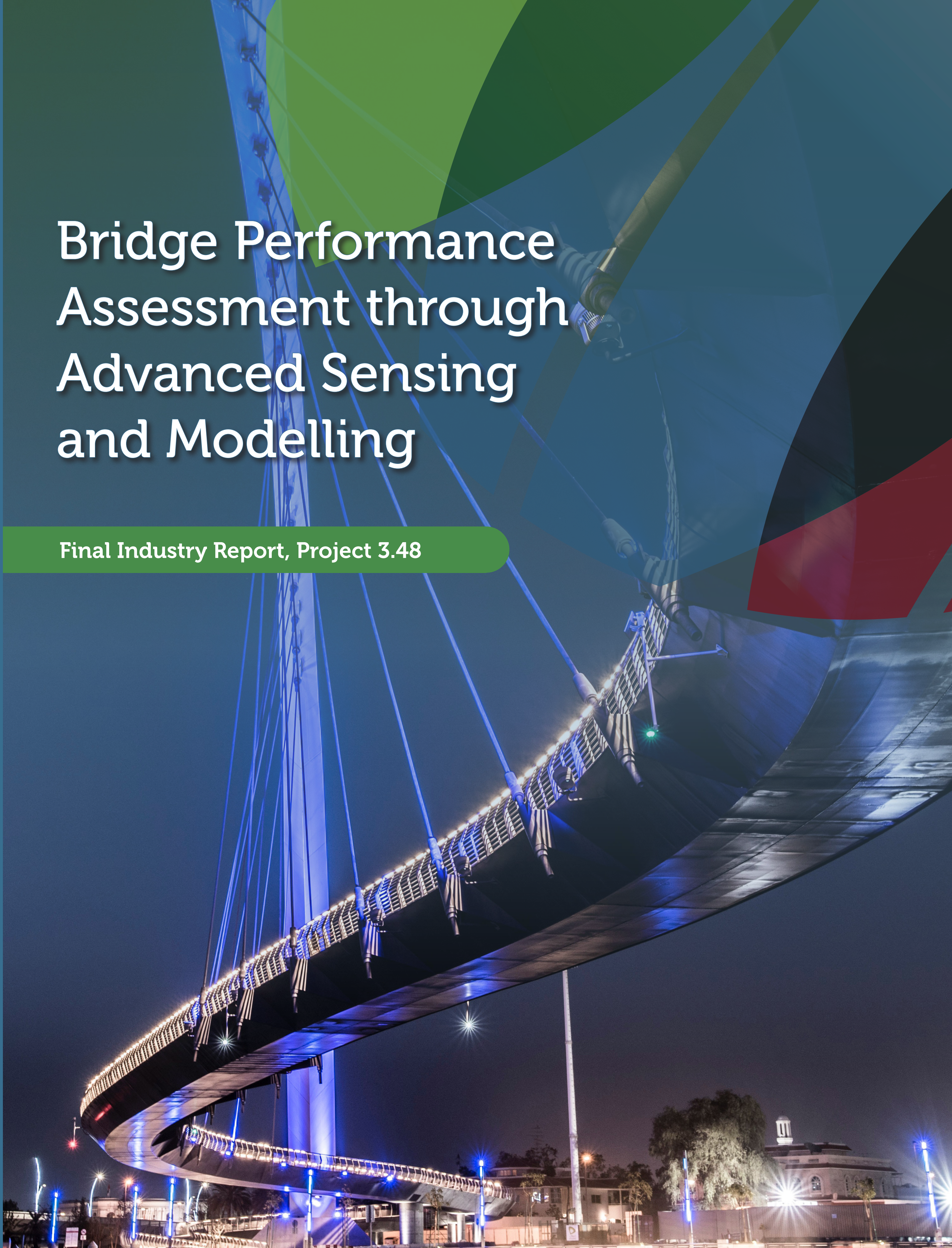
Bridge Performance Assessment through Advanced Sensing and Modelling

Final Industry Report, Project 3.48



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Sustainable Built Environment National Research Centre AUSTRALIA

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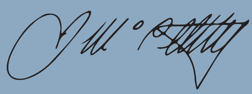
Preface

The Sustainable Built Environment National Research Centre (SBEnrc), the successor to Australia's Cooperative Research Centre (CRC) for Construction Innovation, is committed to making a leading contribution to innovation across the Australian built environment industry. We are dedicated to working collaboratively with industry and government to develop and apply practical research outcomes that improve industry practice and enhance our nation's competitiveness.

We encourage you to draw on the results of this applied research to deliver tangible outcomes for your operations. By working together, we can transform our industry and communities through enhanced and sustainable business processes, environmental performance and productivity.



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Executive Summary

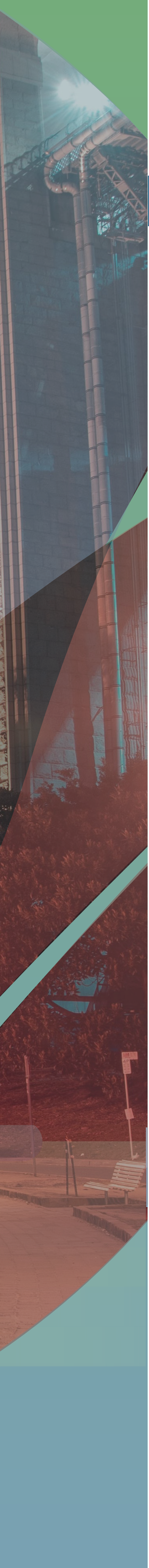
Distress caused by hazard effects and frequent loads is increasingly occurring with time in service and popularised utilisation of large-scale structures. Accurate performance assessment is significant in the management decision-making process for optimal lifecycle performance.

According to the Australian Local Government Association, the Bridges Renewal Program will receive an additional $10 million per year over four years from 2022-23 to 2025-26 to improve the safety and efficiency of critical bridge infrastructure. This brings the Australian Government commitment to this program up to nearly $900 million from 2015-16 and 2025-26, with an ongoing commitment of $85 million per year. Based on the urgent expectation, the key aim of this project is to integrate advanced sensing, modelling, and data interpretation technologies in creating cyberinfrastructure, for bridges particularly, to improve current performance assessment and future capacity estimation.

The objectives included:

- Creating an automated 3D Model through Point Cloud
- Designing a robust wireless measurement system
- Developing an effective data interpretation approach
- Validating the cyberinfrastructure platform

The project helps access actual infrastructure performance and evaluate the reserve capacity of bridges. The expected outputs are to optimise infrastructure management and maintenance planning, reduce redundant interventions, guide infrastructure modifications, and improve the future design. It also helps improve the current maintenance selection and budget allocation of bridge agencies.



Introduction

The qualified civil infrastructure is originally good, but continued neglect of the health state during life could cause fatal disasters. In practice, current performance assessment approaches were weak in data acquisition, assessing the actual infrastructure performance, and evaluating the reserve capacity. Three topics have been determined to ease the current scientific bottleneck in data interpretation, including optimal wireless sensor placement (WSP) for structure monitoring, new methods for monitoring data analysis, and visual management via BIM&GIS, respectively.

Topic No.1 is the optimal WSP for structural health monitoring (SHM). A tool of WSP for bridge SHM was developed on the multi-objective optimisation (MOO) technique and bridge information modeling technology. The tool will facilitate the implementation of wireless-based SHM systems by reducing construction costs, extending lifetime, and improving detection accuracy.

Topic No.2 is the monitoring data analysis of an in-service restressed concrete bridge in Western Australia. The monitoring data from the Bridge No. 1223 in Rockingham was analysed. Modal identification was performed with the measured dynamic data to extract the significant vibration frequencies of the bridge under operational conditions. Lastly, the load-carrying capacity was investigated, based on directly measured responses and the updated finite element model of the bridge.

Topic No.3 is the integration of BIM and GIS in modeling the bridge. Usual tools such as Feature Manipulation Engine (FME) and Data Interoperability Extension for ArcGIS (DIA) are easily to result in information loss. This project proposed an enhanced Open-Source Approach (E-OSA) to realise more reliable data transformation from BIM to GIS in transforming complex models. Management capacity of long-term projects and large-scale regional projects will benefit from the innovative method.

This project employed sensing, modeling, and data interpretation technologies in creating cyberinfrastructure to improve current performance assessment and future capacity estimation. Different from existing work, our method would present all the potential solutions to improve the current maintenance selection and budget allocation of bridge agencies. Furthermore, BIM and GIS have been embedded for visualisation and improving management capacity, which is more practical for civil engineers, wireless engineers, and related sub-contractors.

Industry Deliverables

The project has been delivered to the industry:

- A total monitoring and management platform, covering the following seven service areas: bridge model, regional space management, data acquisition, bridge disease visualisation, maintenance strategy, budget allocation, and management visualisation. BIM and GIS are integrated by an enhanced Open-Source Approach to realise management visualisation and then improve management capacity. The platform is useful to inform the performance assessment and future capacity estimation of agency-specific bridges maintenance. This total monitoring and management platform is innovative because it can present all the potential solutions to optimise the current maintenance strategy and budget allocation of bridge agencies.
- For the structural health monitoring (SHM) industry, new data acquisition and analysis methodologies ensure the quality of data and the accuracy of performance prediction. Analytical response calculates based on ratios with the proposed sensitivity-based model updating method is more accurate compared with the usual half-power bandwidth method. These methods will promote the adoption of SHM in more areas including structural design, space technology, earthquake response analysis and damage prediction, and mechanical system fault diagnosis, etc.
- For the maintenance agency, the methodology and tools to integrate the bridge model and spatial geographic information, which could visualise the treatment strategies and calculate the maintenance cost. It is a representation of the impact of bridge maintenance on bridge users.

Data Sources and Analysis

The methods used in this project were based on internationally recognised evaluation methods, as described below.

The data acquisition for bridge response was supported by the prototype of optimal wireless sensor placement (OWSP), which can reduce construction cost, extend lifetime, and improve detection accuracy. MOO technique was employed due to its great performance to balance the above aims (Sengupta, Das, Nasir, & Panigrahi, 2013). The data obtained was analysed by the sensitivity-based model updating method, which had gained significant attention for structure response analysis of bridges (J. Li, Law, & Ding, 2012). Next, maintenance visualisation was realised by bridge information modelling, based on the integration of BIM/GIS and enhanced Open-Source Approach (E-OSA) (Deng, Cheng, & Anumba, 2016). Maintenance strategies simulation and optimisation on the bridge were mainly dependent on 4D BIM, which has been largely implemented in planning simulation and optimisation (D.-Y. Lee, Chi, Wang, Wang, & Park, 2016). Performance assessment and management capacity of bridges will benefit from the innovative platform.

Data were gathered from various credible sources. While Federal, State, and Local Government data were preferred, other international sources from the World Bank and credible academic databases were included if Australian-specific information could not be identified.

Explanation	Data Source for Bridge Performance Assessment
This report provides the trend and process of research in the development of a bridge assessment tool.	Austroads: Investigating the Development of a Bridge Assessment Tool for Determining Access for High Productivity Freight Vehicles, Research report (2012) https://austroads.com.au/publications/freight/ap-r398-12
This guideline provides the replacement value and annual maintenance expenditure of some bridges in Australia.	Austroads: Guidelines for Ensuring Specified Quality Performance in Bridge Construction (2003) https://trid.trb.org/view/702557
This guideline provides the value of several parameters in the Energy Consumption Model for Optimal Wireless Sensor Placement.	Olariu, S., Stojmenovic, I.: Design guidelines for maximising lifetime and avoiding energy holes in sensor networks with uniform distribution and uniform reporting. In: INFOCOM 2006, pp. 1–12 (2006) https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.410.4763&rep=rep1&type=pdf
The National Building Information Model Standard Project Committee has constructed the standard of BIM.	National BIM Standard-United States. About the National BIM Standard-United States®. Available online: https://www.nationalbimstandard.org/about
This standard specifies a conceptual data schema and an exchange file format for Building Information Model (BIM) data.	ISO, Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries, Available online: https://www.iso.org/standard/51622.html
This standard describes the aim of the development of CityGML, which is to reach a common definition of the basic entities, attributes, and relations of a 3D city model.	G. Groger, T.H. Kolbe, C. Nagel, K.-H. Hafele, OGC city geography markup language (CityGML) encoding standard, Available online: https://portal.opengeospatial.org/files/?artifact_id=47842

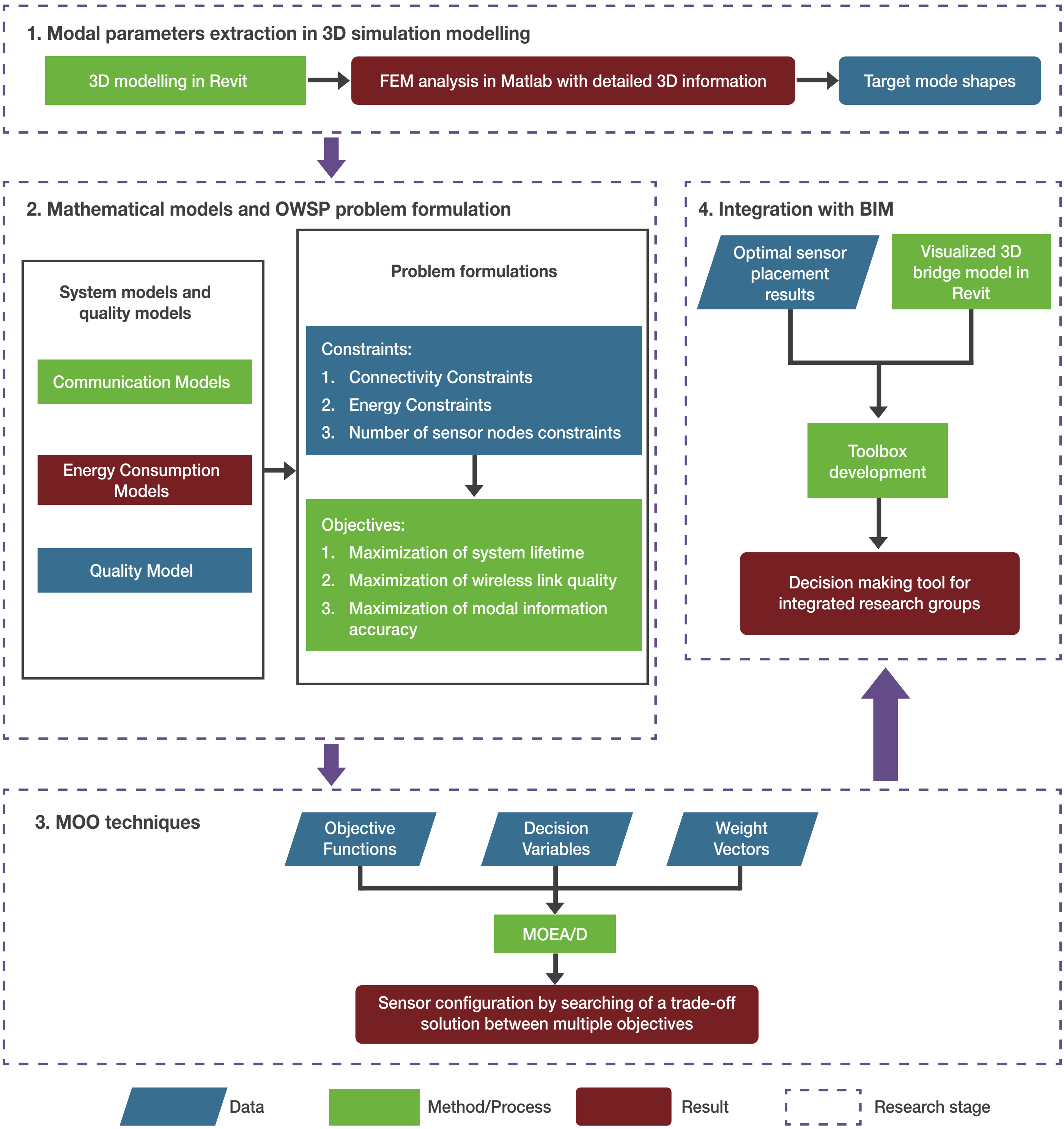
Optimal Wireless Sensor Placement for SHM

The qualified civil infrastructure is originally good, but continued neglect of the health state during life could cause fatal disasters. In Australia, over 60% of bridges on all local roads are used for over 50 years and approximately 55% of all highway bridges are used for more than 20 years (Australia, 2012). However, the current engineering practices based on wire-based SHM systems require a tremendous labour cost and implementation time. For example, the cost of the wire-based SHM systems deployed on the Bill Emerson Memorial Bridge and TsingMa Bridge reach $1.3 and $8 million (Wong, 2004). There are around 22,500 bridges with a replacement value of about AUD $3 billion, and an annual maintenance expenditure of about AUD$300 million in Australia (Roberts, CARSE, FENWICK, & CLIFFORD, 2003). The increasing demand for SHM systems promotes cost-effective and easily deployed wireless-based SHM systems as substitutes for conventional wire-based SHM systems. Installation and maintenance costs can be reduced from several thousand dollars per sensing channel to $100 per channel in the wireless-based SHM (Lynch & Loh, 2006). How to develop an approach of OWSP for wireless-based SHM systems considering construction cost and wireless transmission quality is important, especially on large-scale structures.

The objective of this work is to create a framework by integrating our new approach of OWSP based on developed MOO techniques with bridge information modelling (BrIM) technology so that optimal sensor placement locations can be visualised and discussed in integrated research groups in the design stage. The research consists of 4 stages:

- 3D model creation and modal parameters extraction;
- Development of wireless-based SHM system models consisting of communication model (CM), quality model (QM) of structure and energy consumption model (ECM);
- Using MOO technique for determining optimal sensor placement locations;
- Integration with BrIM software in the first stage, the 3D model will be created through 2D drawing.

Different from existing work, our method will present all the potential solutions on OWSP to be discussed by all research teams before making the final decision. Besides, the visualised results of solutions on OWSP could be more practical for civil engineers, wireless engineers, and related sub-contractors.



Note: General framework for developing the tool

New Method of Structure Response Analysis

Distress caused by hazard effects and frequent loads is increasingly occurring during the life of a bridge. For example, from the public report between 2009 and 2012, 8 bridges collapsed in China and more than 20 people dead in these accidents. In the United States, 1254 bridge failures that occurred from 1980 to 2012 have been reported (G. C. Lee, Mohan, Huang, & Fard, 2013). Thus, the condition and reliability assessment of bridges generate great attention all over the world. Study on the OWSP will ensure the quality and efficiency of the data acquisition. How to use the monitoring data in the performance assessment of the bridge is also a challenge in the construction industry.

The key to this research is an effective estimation method for damping ratios, which is a significant parameter in predicting and analysing the dynamic behaviour of a bridge. Other system properties such as mass, properties such as mass, and stiffness can be determined via system identification of structures. But the traditional non-modal based method is difficult to identify the damping of the high-frequency modes of the bridge because these modes are difficult to excite.

Therefore, the sensitivity-based model updating method for damping identification with vibration measurements has been adopted in this project. Damping ratios identification by the proposed method was performed through an iterative process to match the analytical response with the measured response (X. Li & Law, 2009). The analytical response based on the sensitivity-based model updating method is more familiar with the experimentally measured response, compared with the popular half-power bandwidth method.

For bridges and other large-scale engineering structures, a slight difference between the actual and estimated damping ratios may produce a significant difference in vibration response prediction. In Australia, over 60% of bridges on all local roads are used for over 50 years and approximately 55% of all highway bridges are used for more than 20 years (Australia 2012). The effective estimation method for damping ratios will benefit the bridge in the structural design, space technology, earthquake response analysis, damage prediction, etc.

Response duration(s)	With damping ratios by half-power bandwidth method	With damping ratios by the proposed approach
1	9.02%	7.64%
2	12.39%	11.26%
3	17.66%	15.67%
4	22.87%	20.11%
5	43.34%	24.34%

Note: The relative errors in the measured and analytical responses with identified damping ratios by half-power bandwidth method and the proposed approach

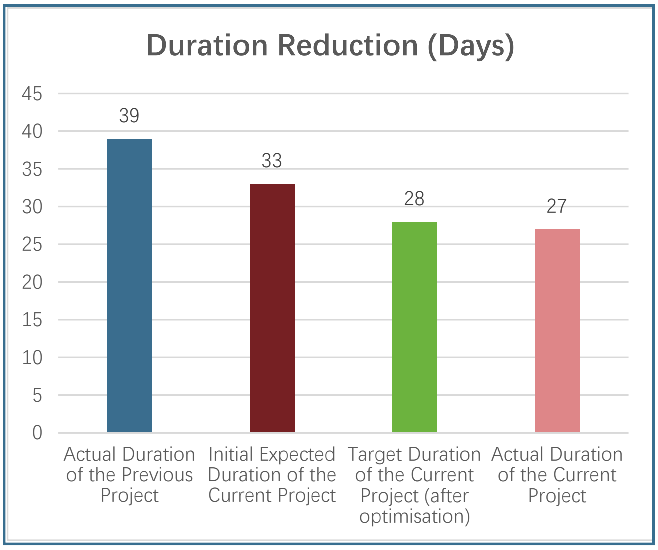
Visualisation Platform Based on the Integration of BIM/GIS

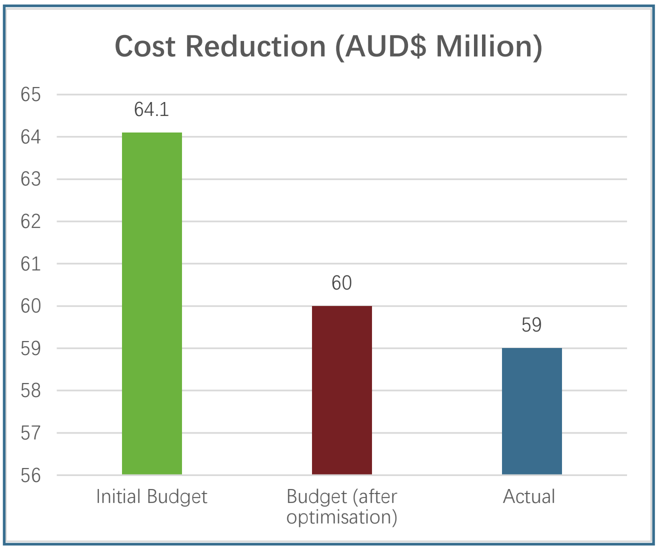
Cyberinfrastructure is a significant part of the smart city, which has great significance in the future of human society. Advanced sensing and modelling were adopted to develop an innovative approach for bridge infrastructure performance assessment and reserve capacity estimation. First, laser scanning was developed to create a refined 3D model for the existing infrastructure to minimise the initial structural construction errors. Then, optimal Wireless Sensing was planned to acquire the vibration measurement data for infrastructure performance assessment and analysis. Next, in-situ Data Interpretation was conducted to assess the infrastructural condition and estimate reserve capacity with considerations of system uncertainties under the operational environment. Finally, BIM was developed on laser scanning and integrated with GIS into the platform for effective maintenance planning and decision making through visualising and interacting with the above three parts. Result from a real turnaround maintenance project validated the great performance of the platform.

It is argued that there should exist a comprehensive, reliable and practical approach for data interaction between BIM and GIS.

The most relevant 3D data formats involved in BIM and GIS are Industry Foundation Classes (IFC) and multipath (shape file), respectively. Commercial tools are prone to fail or result in information loss when semantics mismatches exist. An enhanced open-source approach (E-OSA) have been employed for transforming IFC into shape file, which is more reliable in transforming complex models. All shape representations of building elements can be retained during transformation. Besides, there is no geometric information loss during transformation using the proposed method.

In the proposed platform, performance assessment and reserve capacity estimation are based on the structural response and the traffic-related environment. GIS could analyse and visualises location-related problems of bridges in geospatial science. Besides, maintenance strategies could be visualised for effective planning and decision-making. Performance assessment and management capacity of bridges will benefit from the innovative platform.





Industry Benefits

A key challenge of this research was to demonstrate how the platform and tools developed in this project can be implemented in real projects.

This project has demonstrated industry value for bridge agencies at various levels, including:

- An innovative monitoring and management platform which integrates performance assessment, capacity estimation, and maintenance optimisation. It presents a more accurate performance assessment and capacity estimation for the bridge than the traditional methods.
- A low-cost, advanced, and propagable method for structure monitoring and response analysis for the bridge. Installation and maintenance costs in the wireless-based SHM can be reduced from several thousand dollars per sensing channel to $100 per channel, compared with traditional wire-based SHM systems. According to the Australian Local Government Association (2021), there is new funding of $250 million has been announced for the Bridges Renewal and Heavy Vehicle Safety and Productivity Programs. The approach developed in this project significantly addresses the urgent by supporting bridge performance assessment with lower installation and maintenance costs and a more propagable method.
- Provision of reliable and accurate maintenance treatments, addressing the Australian Government's strategic direction, optimising maintenance investment. Because maintenance plans generated will be based on accurate damage prediction via new analysis methods, and maintenance simulations via BIM/GIS technology. It ensures that optimal budget allocation and maintenance resources will be allocated to specific maintenance activities at the right location and time.
- A new sustainable management mode for bridge infrastructure. This project will improve upon the conventional methods for bridge maintenance, reducing labor cost and time required for inspections and helping to establish efficient training processes for inexperienced engineers through efficient modeling, robust analysis, and intuitive visualisation. The proposed model is more practical to improve the management capacity of the bridge for civil engineers, wireless engineers, and related sub-contractors compare with the traditional approaches.

Conclusions and Next Steps

This SBEnrc research project has developed an innovative monitoring and management platform for the bridge, providing necessary frameworks and tools to improve current performance assessment, future capacity estimation, and maintenance strategy optimisation:

- A prototype of OWSP has been developed for the data acquisition for bridge response, considering deployment cost, service life and detection accuracy. MOO technique was employed due to its great performance in determining the optimal result of the above aims. The reliable and practical tool of OWSP can promote the implementation of wireless-based SHM systems to more adoption in the bridge agencies.
- The sensitivity-based model updating method has been investigated to identify damping ratios from the data acquired by OWSP. This method provides an effective data interpretation approach for a more accurate performance assessment and capacity estimation of the bridge.
- The 4D BIM of the bridge was conducted for damage prediction and optimal maintenance planning. Benefits such as time and cost reduction and safety improvement are calculated and explained to improve the maintenance treatments. The schedule will be simulated based on the platform and then determined by owners.
- Location-related problems in geospatial science have been analysed and visualised by GIS, which could provide more macro guidance on bridge management through various spatial analysis tools. Integration of BIM and GIS will promote the digitisation and intelligence of social development. The feedback from the proposed framework can guide infrastructure modifications, and improve the future design.

Advanced sensing, modeling and data interpretation technologies have been integrated for the safety, economic, and efficiency considerations of performance assessment and maintenance optimisation.

Our industry partners have adopted these methods and their reliability and efficiency have been verified in our investigations. Moving forward, we encourage more industry practitioners to implement these frameworks and provide valuable feedback to realise the full potential of cyberinfrastructure.

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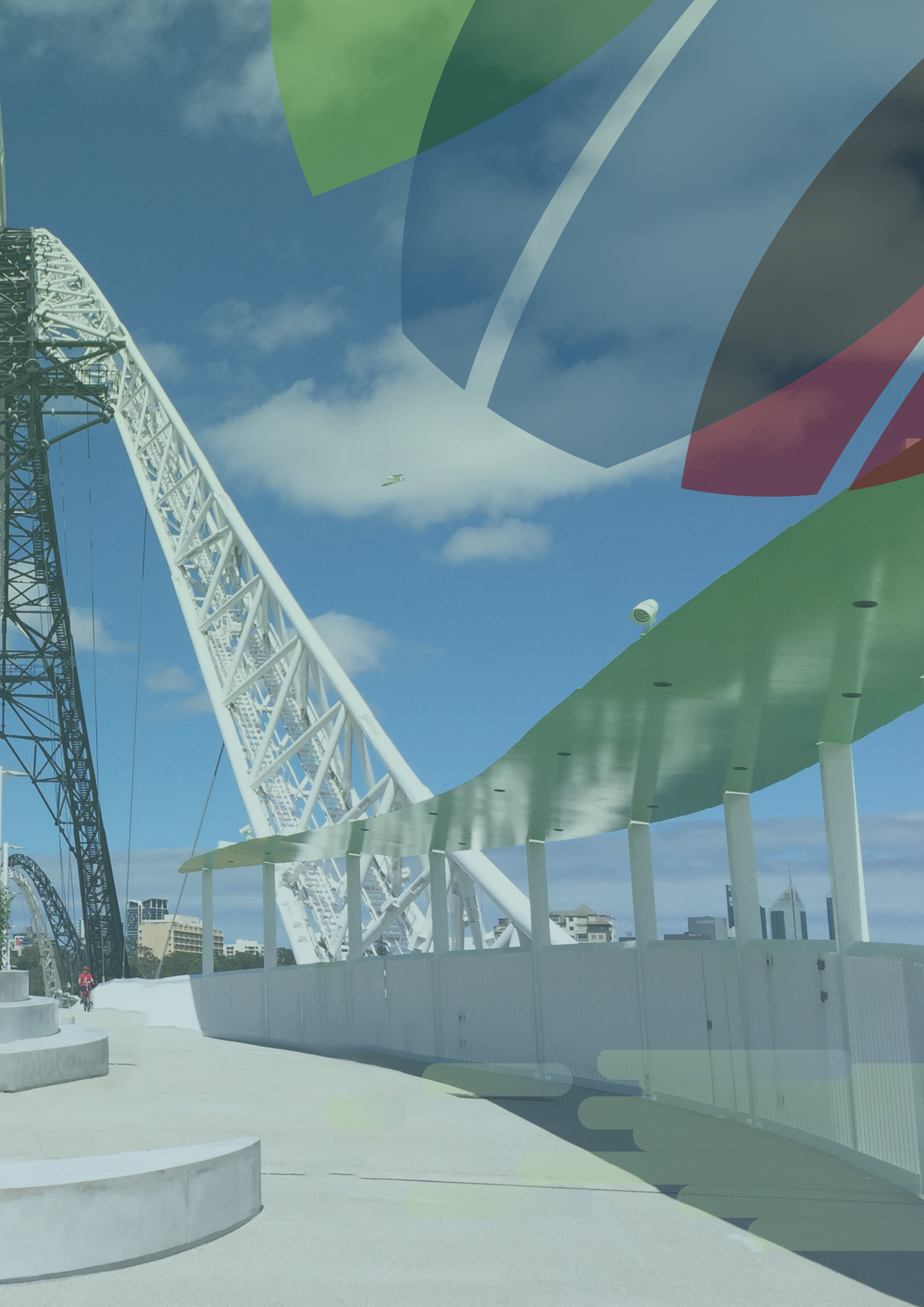

Find out more:

Project webpage:
https://sbenrc.com.au/research-programs/3-48arc/

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