Leveraging an Integrated Information Lifecycle Management Framework

Building and Infrastructure Sectors

FINAL INDUSTRY REPORT, PROJECT 2.72

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Message from the Chair

"This project addresses the industry challenge of structuring and integrating quality data for key decision making to create a centralised view of data requirements and how they will be used in project lifecycle, including housing portfolio asset management and road maintenance. This was achieved through a series of representative case studies and an innovative approach to employing machine learning methods. The success of the project results from a productive partnership among research, industry and policy agencies. This has been a successful project and now provides the springboard for development of a unified digital engineering solution through a structured and integrated data approach which has national consistency and overseas compatibility."

Steve Golding, AM
Chair, Project Steering Group

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 organisation. By working together, we can transform our industry and communities through enhanced and sustainable business processes, environmental performance, and productivity.

John V McCarthy AO
Chair, Sustainable Built Environment National Research Centre

Dr Keith Hampson
CEO, Sustainable Built Environment National Research Centre

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Executive Summary

Digital engineering in the built environment has been the subject of changing practice and research for years and is often complicated by inconsistency in data standards from various stakeholders. This project seeks to examine the industry best practices and international standards related to structured and integrated data and develop a practical approach that can efficiently guide industry people to structure their data by leveraging the existing well-established data standards. This will aid the wider adoption and consistent curation of digital information for maintaining and operating assets across the construction supply chain, improving the efficiency of managing community assets, improving the return on investment and ensuring sustainability, resilience and safety.

This project will respond to the previously identified needs of industry for a shared and consistent approach and most importantly, its implementation to transfer BIM/DE data from one solution to another without the need to map every model and tool, which may differ from stakeholder to stakeholder.

The specific objectives are to:

1. Address the industry challenge of structuring and integrating quality data for key decision making to create a centralised view of data requirements and how they will be used in project lifecycle, including housing portfolio asset management and road maintenance;
2. Investigate how data (digital or non-digital) can be used to better understand the impacts of decisions by developing a data-driven decision making framework; and
3. Facilitate education for industry and the broader community on the needs and methods of structured data in project lifecycle to achieve efficiency and resilience. This will help to prepare for the wide adoption of building information modelling and digital engineering in the housing, building and transport sectors.

It is expected that outputs can be implemented to assist the integration of innovative technologies and approaches, and these include BIM and machine learning for effective lifecycle management of building, housing and infrastructure projects.


TUNNEL
LOW CLEARANCE 4.4m
PENALTY EXCEEDS $2000
AND LOSS OF REGISTRATION

Introduction and overview of case studies

This case study report aims to demonstrate how information and data can be collected, exchanged, stored and used at various life cycle stages of building and infrastructure projects, supported by the latest digital engineering technologies and approaches.

The first case study focuses on the use of latest machine learning technologies to address the information exchange between human and computers. With the support of emerging digital engineering technologies, the volume of data and information increases significantly. A pavement crack case study is selected. This case study aims to interpret the experts' knowledge through the information collected by laser crack measurement systems.

The second case study aims to investigate best-practice technologies and information management strategies for heritage assets and their unique preservation and restoration requirements. The exploratory work and guidance produced aims to form a more detailed asset information management strategy for heritage assets.

The last case study aims to investigate the reasons leading to the resistance of change from the construction industry when implementing BIM and propose potential educational frameworks to ensure that the BIM team and contractors have the same level of understanding on information delivery in BIM to improve efficiency.

Data-driven pavement crack monitoring and analysis

BACKGROUND

The surface condition of pavement is a critical consideration in evaluating the overall pavement condition, based on which maintenance decisions can be made to ensure that the road network can continuously support the community.

According to Austroads (2006), crack is defined as unplanned break or discontinuity in the integrity of the pavement surface. It can be a narrow opening or partial fracture, often indicating vertical splitting of the pavement. Crack data of pavement can serve the following purposes:

1. Condition monitoring for the whole road network;
2. Selecting appropriate maintenance strategies based on crack condition;
3. Life cycle costing analysis and other structural analysis of pavement; and
4. Developing improved deterioration models for pavement.

Human inspection is one of the commonly adopted methods to evaluate pavement crack condition. This type of human inspection is often referred to as the manual method. The manual method requires inspectors to either drive over or walk over the road lanes to assess crack condition. According to Main Roads Western Australia (MRWA), the criteria that are considered in manual inspection checking include block cracking, crocodile cracking, transverse cracking, diagonal cracking, meandering crack, longitudinal cracking and extent of cracking After the assessment, an overall crack condition score is obtained with 1 being perfect pavement crack condition with no cracks at all and 5 being severe pavement crack condition with a significant number of cracks being observed.

Recent advances in digital technologies provide automatic ways to detect pavement crack data and analyse pavement crack condition. Road agencies, including MRWA, now collect such data, at traffic speed, using systems such as Hawkeye Automatic Crack Detection (ACD), based on Laser Crack Measurement System (LCMS), provided by Pavemetrics in Canada. Figure 1 provides an example of the data collected through such automatic system. As can be seen from Figure 1, the LCMS, which uses laser line projectors, high speed cameras and advanced optics to acquire high resolution 3D profiles of the road, can be applied in real time to recognise and categorise the cracks, which are colour coded and can be exported in other data formats, such as .CSV files.

CASE STUDY OBJECTIVES

Human inspection provides an intuitive way to understand pavement crack condition and is still commonly used. The experts' knowledge through human inspection are highly valued and the single score given after human inspection is a straightforward indicator to understand pavement crack condition. The single score, rating from 1 (perfect crack condition) to 5 (severe crack condition), represents the crack condition of the whole road segment, which can range from several hundred metres to several kilometres.

On the other hand, the automatic system, specifically the LCMS in this study, reports cracks in 10m intervals. The system works in such a way (use with Figure 1 for understanding how the system works):

1. One pavement scan is taken every 10m interval.
2. The scan is divided into three channels: outer wheel path, between wheel path and inner wheel path. Each channel is 1m wide. This means that the scan can only capture cracks that are within the 3m footprint. It cannot capture cracks outside of the 3m footprint to the trafficable width.
3. The cracks are analysed on a square metre basis, i.e. a 1m x 1m frame. In each channel, there are 10 frames and in each image, there are 30 frames to analyse. Cracks, including longitudinal, transverse and crocodile cracks are identified.

The two methods are different in a few ways. First of all, human inspection is to report crack condition for the whole road segment, which can range from several hundred metres to several kilometres. On the other hand, the automatic approach reports crack condition in every 10m interval. In addition, human inspection, based on experts' knowledge, reports a single crack condition score which is extremely useful for making informed decision, such as maintenance budget allocation, while the automatic approach, although reporting detailed crack condition, does not provide such score. It is therefore important to understand how the crack condition, provided through the automatic system, is correlated to the human inspection. This case study therefore aims to interpret the experts' knowledge through LCMS using machine learning technologies.

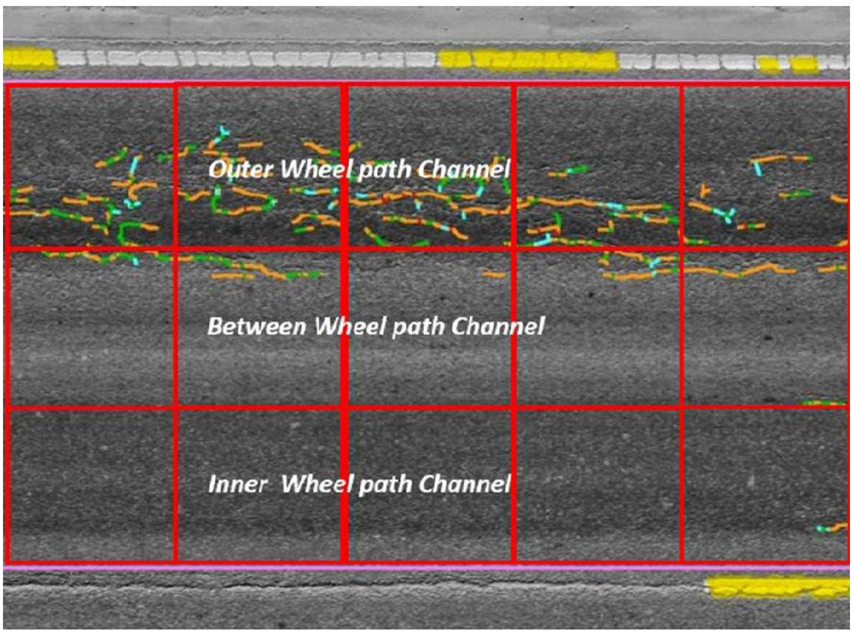


Figure 1 *An example of the image collected by the automatic system (Source: MRWA, 2018)*

METHOD & RESULTS

The Wheatbelt region is selected as the case study. Figure 2 and Figure 3 show the distribution of human inspection and automatic inspection data of the region. As can be seen from Figure 2, the Wheatbelt region has a balanced visual inspection scores. Figure 3 shows the crack data, including crack severity (crack width per frame) and intensity (crack length per frame) of the outer, inner and between wheel path.

Random forest, a machine learning method, is used to interpret and explain the correlation between human visual inspection and real-time crack data collected through LCMS. This machine learning method is then compared to a traditional linear method to demonstrate the accuracy of the explanation.

Figure 4 shows the accuracy of the algorithm developed through Random Forest for predicting a crack score that is consistent with a visual inspection. 69% Random Forest predicted cracking scores are consistent with visual inspections. The consistency ratio between the linear model, pre dicted score and visual inspections is only 23%.

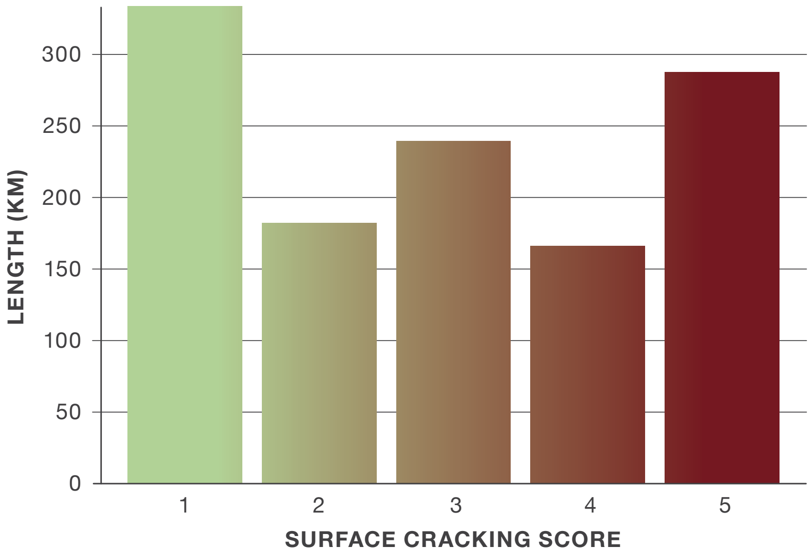


Figure 2 *Visual inspection data*

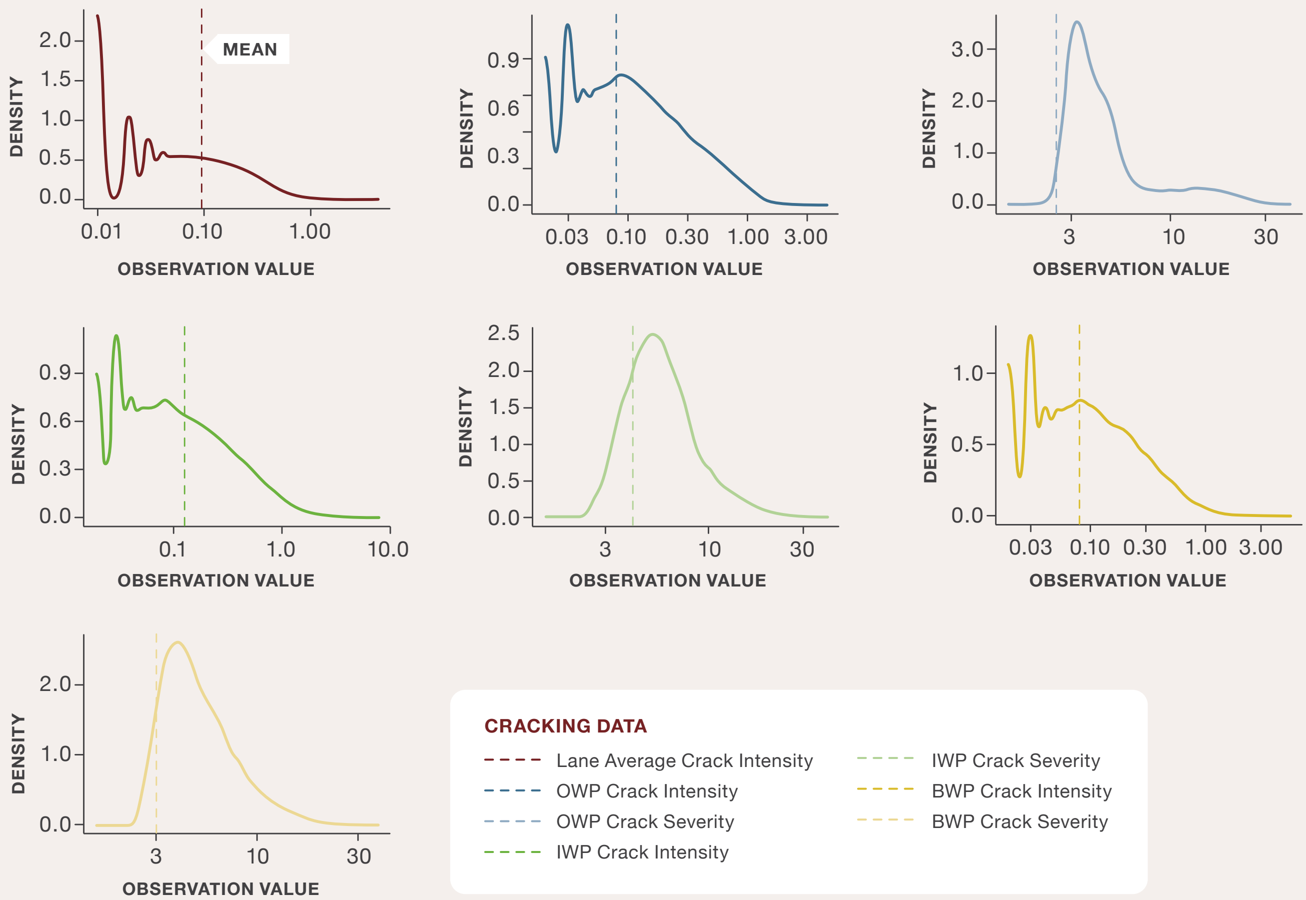


Figure 3 *Distribution of crack data obtained through the automatic system*

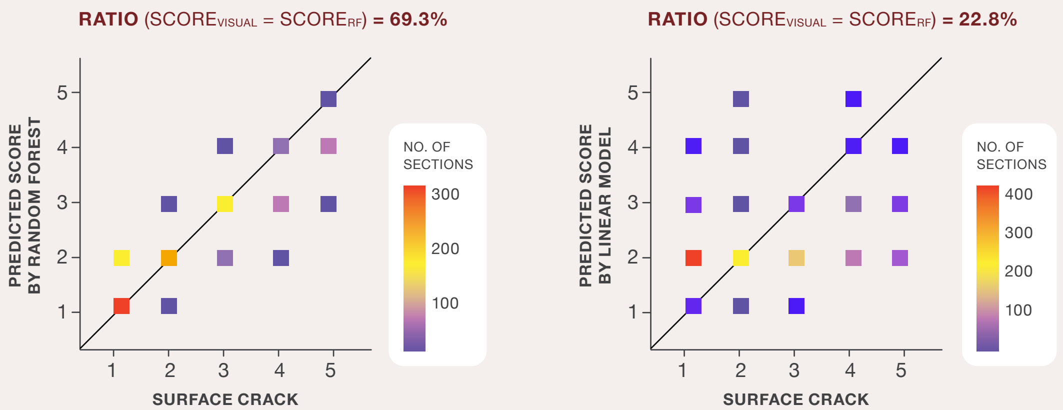


Figure 4 *The consistency of the Random Forest method compared with a traditional linear approach*

As the Wheatbelt region's visual inspection is conducted by two separate inspectors. We then analyse whether these two inspectors (editor M and editor S) rate crack condition consistently and whether our developed algorithm is able to predict accurately an overall crack condition score using the LCMS data. Figure 5 shows the results. Machine learning provides more accurate modelling for both inspectors (M and S) than linear models.

Linear models show that the inspection of Editor M is more accurate in roads of high cracking scores (e.g., 2, 3), and the inspection of Editor S is more accurate in roads with low cracking scores (e.g., 1). If we differentiate inspectors, the accuracy of machine learning can be critically improved, but the accuracy of linear regression is similar with the combined data.

The algorithm is then tested and validated at the Goldfields-Esperance region (see Figure 6). The results show an overall 68.7% accuracy, indicating the validity of the approach. Great Southern Region East and Great Southern Region West are also included in the validation but because the raw human inspection data are heavily skewed, the results are for reference only.

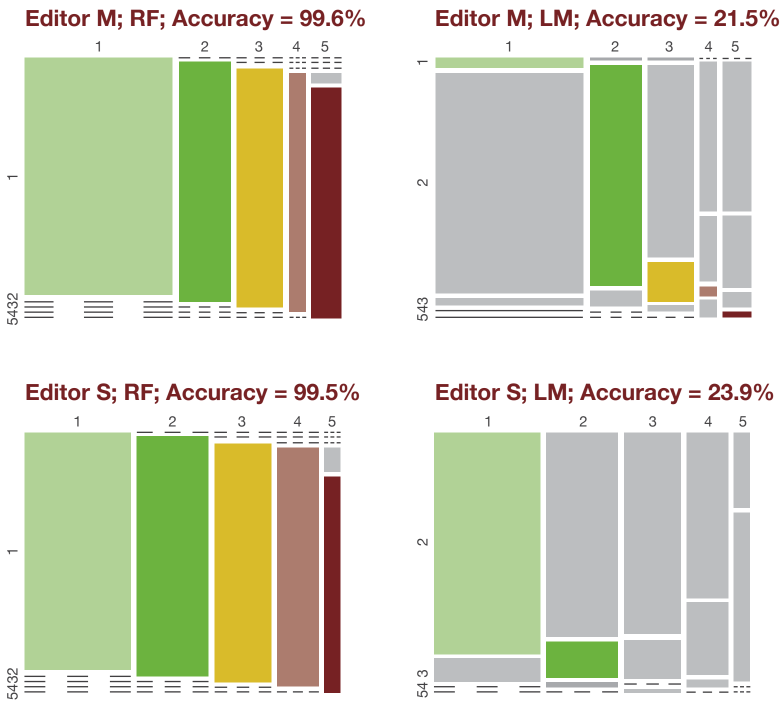


Figure 5 *The accuracy of prediction of editor M and editor S using the machine learning method and linear method*

Region		No	Machine learning (random forest)	Linear regression
Wheatbelt		1119	69.3%	22.8%
	Inspector M	558	99.6%	21.5%
	Inspector S	561	99.5%	23.9%
Goldfields-Esperance		983	68.7%	25.4%
Great Southern Region East		252	93.6%	42.8%
Great Southern Region West		790	86.2%	21.6%

Figure 6 *A summary of the accuracy of the machine learning method and linear method in predicting an overall crack condition score*

CONCLUDING REMARKS AND RECOMMENDATIONS

1. Traditional human-based pavement condition inspection can be subjective and labour-intensive. Automatic detection methods have been developed in recent years to support human inspection. With the support of latest laser scanning technologies, there is a great volume of data related to pavement cracks that need to be processed and analysed for guide decision making. This case study has the below major findings: Matching learning methods, compared with the traditional linear methods, are effective in predicting the visual inspection scores that are currently used for decision making. The accuracy rate is at approximately 68%-70%, much higher than the 22%-25% accuracy rates of linear regression.
2. The method can provide even more accurate results when the visual inspection is conducted by a single inspector or inspectors that have consistent inspection behaviours. The results show that the accuracy can be improved to 99%.

Such findings provide useful insights. First of all, there can be an algorithm developed for predicting the visual inspection scores based on the crack data obtained from the automatic crack detections system. Such prediction has two distinct advantages, i.e. it has the objective data that can be collected in an automatic and less labour intensive way and the outcome of the prediction is a single visual inspection score of each road segment that can be more readily used in decision making than the raw crack data. It is also recommended that the rating behaviour of the various inspectors be further analysed so that discrepancies among visual inspection practices can be identified and follow up trainings can be developed.

Managing Heritage Assets: Vision for Heritage BIM (HBIM)

BACKGROUND

Historic assets provide economic benefits firstly through tourism generated from domestic and international visitors, and secondly, through the repair and maintenance of historic buildings that provide construction economic output for preservation (Historic England, 2019). With streamlined maintenance and repair management plans, the tourism and construction economic outputs can be increased significantly. Moreover, the Taskforce of the Commonwealth, State, and Territory (Taskforce, 2004) states that heritage assets serve as community 'touchstones' that inform and educate the public about the significance of the heritage asset. The purpose of conserving these sites is to enrich the cultural heritage of the nation and promote access to cultural heritage (Historic England, 2019).

The information and data involved in heritage asset management can be represented in a variety of formats and several different locations. Heritage Building Information Modelling (HBIM) can incorporate multiple types of data, such as cultural and historical significance, building plans, maintenance schedules, or any other relevant information available.

Over the last few decades, Building Information Modelling (BIM) standards and guidelines have been adopted and implemented by the Architecture, Engineering, and Construction (AEC) sector due to its increasing effectiveness in organising information and modelling data (López et al., 2018). However, the concept of HBIM in Australia is in the initial stages without any proposed guidelines to manage Australia's heritage sites. Therefore, BIM guidelines must be developed and implemented into the heritage asset management process to ensure preservation and the presence of proper restoration requirements.

The purpose of this research project is to develop preliminary guidance for implementing data capture and modelling techniques for managing heritage assets for the Queensland Department of Energy and Public Works (Queensland Department of Energy and Public Works). The guidance would allow the department to enhance the lifecycle asset management specifically for heritage assets as they are tailored for the unique preservation and restoration requirements of heritage assets. Due to the absence of information on HBIM in Australia, this project also serves as a literature review of HBIM information, summarising guidelines and industry best practices in countries that have already applied BIM to heritage cultural sites.

CASE STUDY OBJECTIVES

Ultimately, this research project aims to recommend best-practice technologies and information management strategies for Queensland Department of Energy and Public Works's heritage assets and their unique preservation and restoration requirements. The exploratory work and guidance produced aims to assist Queensland Department of Energy and Public Works to form a more detailed asset information management strategy for their portfolio of heritage assets.

The research objectives include:

- Reviewing academic literature surrounding BIM-based processes and the current standards and guidelines that highlight BIM best practices for lifecycle asset management applications, with a focus on heritage buildings.
- Reviewing case studies on HBIM applications to capture valid information regarding the benefits and challenges of HBIM.

In this study, the data collection involves reviewing case studies of HBIM application and conducting semi-structured interviews with Queensland Department of Energy and Public Works representatives to gather more qualitative data.

METHOD

In this case study, we first reviewed case studies in different countries, which can assist in developing knowledge regarding the possible challenges, feasibility of implementation, and overall effectiveness of HBIM. Four case studies have been selected to review the implementation of HBIM for heritage asset management. These case studies were chosen due to their successful application of BIM and because the chosen heritage assets are in the same or similar class of heritage listings as ones managed by Queensland Department of Energy and Public Works.

Four case studies were reviewed, including:

1. **Waverley Station.** Waverley Station was the largest train station in the United Kingdom until Waterloo Station opened in 1921. The main area of interest for BIM was the ticket office and adjacent staff areas at the station; the survey encompassed two floors and was to include the roof and concourse areas (Historic England, 2017). An architectural and building consultancy company named AHR was contracted to undertake the survey and develop a BIM model of the station (See Figure 7).

Figure 7 *Waverley Station: Section view through the laser scan Point Cloud (Source: Historic England, 2017)*

Figure 8 *Woodseat Hall: 3D model (Source: Historic England, 2017)*

2. **Woodseat Hall.** Woodseat Hall was built in 1767 as a home for the High Sheriff of Derbyshire and is south-west of Rocester, in Staffordshire (Historic England, 2017). Following the death of the High Sheriff, the ownership of the asset was contested for 40 years, leading to the decline of the structure's health. When JCB purchased it in 1986, the hall was in a dire state. The overall symmetrical design of the asset is still noticeable in its current condition, while the main body of the building has deteriorated to a point where it is almost unrecognisable. In November 2016, JCB contacted Bridgeway Consulting to undertake surveys to assist with the application process of a planned restoration of the Hall and transformation into a golf clubhouse. The client requested the capture of all structural defects and major architectural features. The three-dimensional geospatial information of the asset was gathered through laser scanning, specifically Leica ScanStations P30 and C10. See Figure 8 for the 3D model developed.

3. **Durham Castle and Cathedral.** Durham Castle is in the city of Durham, England, and it was built in 1093 for a community of Benedictine monks (Tapponi et al., 2015). Currently, Durham Cathedral mainly serves as a tourist destination and a place of pilgrimage and worship. The current cost to maintain the cathedral is £60,000 per week, and it holds 1,700 services a year (Tapponi et al., 2015). The facility manager of the Cathedral decided to change the workflow of the asset through the application of BIM. It allowed them to decrease the cost of renovation and maintenance and make the process more efficient and sustainable. BIM was chosen to transition the traditional methodology of information management to a new approach involving a 3D model and digital information. Laser scanning was determined as the most suitable methodology for geospatial information capture. Figure 9 shows 3D model created.
4. **Nasif House.** Nasif House is located in Jeddah, Saudi Arabia, and was built in 1881 for the then-governor of Jeddah and their wealthy merchant family. Most components of the heritage asset within Jeddah suffer from issues related to their management, conservation, documentation, and monitoring of this important building sector (Baik, 2017). The selection of BIM was driven by the advantages that BIM provides preservation, conservation, and maintenance. The case study primarily focused on two factors, namely the level of detail and the project delivery time.

Semi-structured interviews were conducted to gain further information regarding the current systems in place for heritage asset management at Queensland Department of Energy and Public Works. An interview protocol was created before the interviews to ensure the proper collection of information. The questions were predominately based on the current practices and guidelines in place for the heritage asset information management processes at Queensland Department of Energy and Public Works.

Four key stakeholders were identified. The participants were from the Queensland Government Accommodation Office within Queensland Department of Energy and Public Works; their roles were the following:

- Director of Asset Portfolio
- Principal Asset Manager of Property Group
- Assistant Director of Property Group
- Principal Project Manager of Property Group

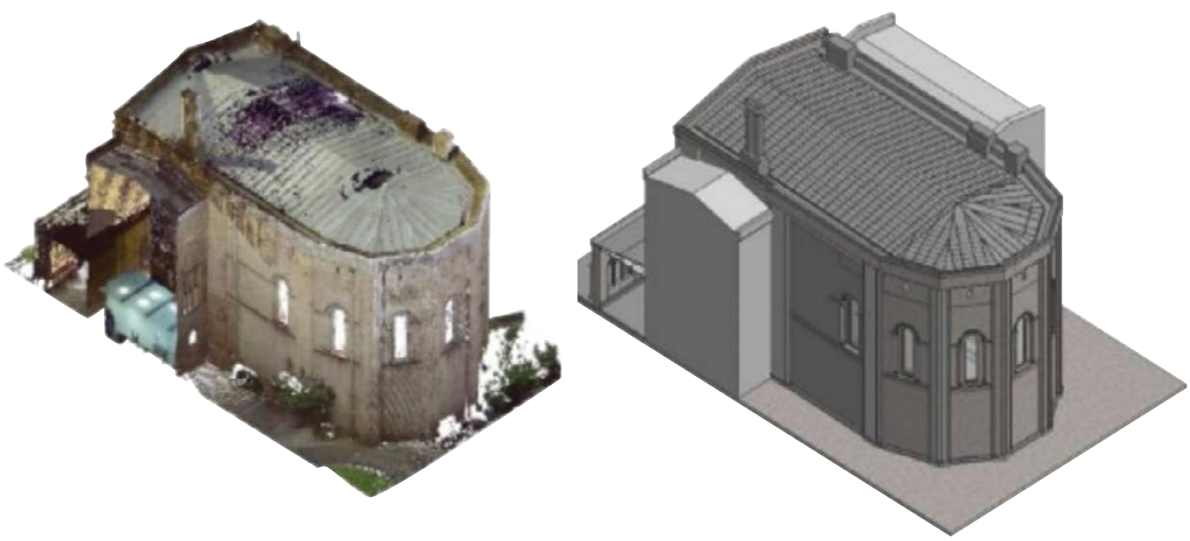


Figure 9 *Durham Castle and Cathedral: 3D model created by Point Cloud scans (Source: Tapponi et al., 2015)*

KEY RESULTS

1. Available technologies

Although the heritage assets reviewed are similar, differing methods of capturing information were used across the studies. All the case studies had similar deliverables and outputs.

A common deliverable was a 3D model to visualise the geometric data captured. The pairing of qualitative information with a 3D model is defined as a 'smart' model (Historic England, 2017). Few of the projects actively used a smart model to visualise further information related to deterioration, maintenance schedules, and so on. Table 1 presents the methodologies used and information captured for each case study.

Table 1 Utilised methodologies and information for case studies:

	CASE STUDY			
Methodology	**Waverley Station**	**Woodseat Hall**	**Durham Cathedral**	**Nasif House**
Terrestrial laser scanning	✔	✔	✔	✔
Photogrammetry				✔
Total station survey	✔	✔	✔	✔
Manual survey				
Semantics				
Parametric modelling	✔		✔	✔
Asset pathology				
Performance data	✔			
Level of Detail	High	Medium	High	High

2. HBIM Guidance

Within the industry, the main obstacles to the adoption of HBIM are funding and time constraints. Although there is evidence that HBIM has long-term benefits related to cost and time management, the initial resources required to implement HBIM act as a deterrent for many departments. Therefore, the guidance developed within this project aims to assist with the initial implementation of HBIM for managing heritage assets by consolidating all information relevant to HBIM and developing four levels of maturity. The guidance is developed based on the four levels of HBIM implementation. The levels range from Level 1, the lowest level of HBIM implementation, to Level 4, the highest current HBIM implementation possible. The key criterion defining each level is the level of detail of the final HBIM model produced. Figure 10 shows the features of each level of HBIM. The levels of HBIM are detailed in the following subsections (See Figure 10).

HBIM Level 1 characteristics:

- It is the lowest level of HBIM implementation that features entry-level technology to begin the process of updating existing heritage management practices with updated BIM software and technologies.
- It marks the initial steps towards moving to a basic level of HBIM collaboration.
- It features the collection of available historical and archaeological information but does not investigate further.
- It features the development of a 3D model; however, the use of high-end technology is not feasible, so manual surveys and photographs may be used as supporting evidence to manually produce a model.
- The level of detail within the 3D model is low, and only the main aspects and proportions of the heritage asset are featured to make it recognisable.
- The heritage assets most suitable for Level 1 of HBIM are those that are non-iconic and do not produce enough economic impact to validate a high level of HBIM.

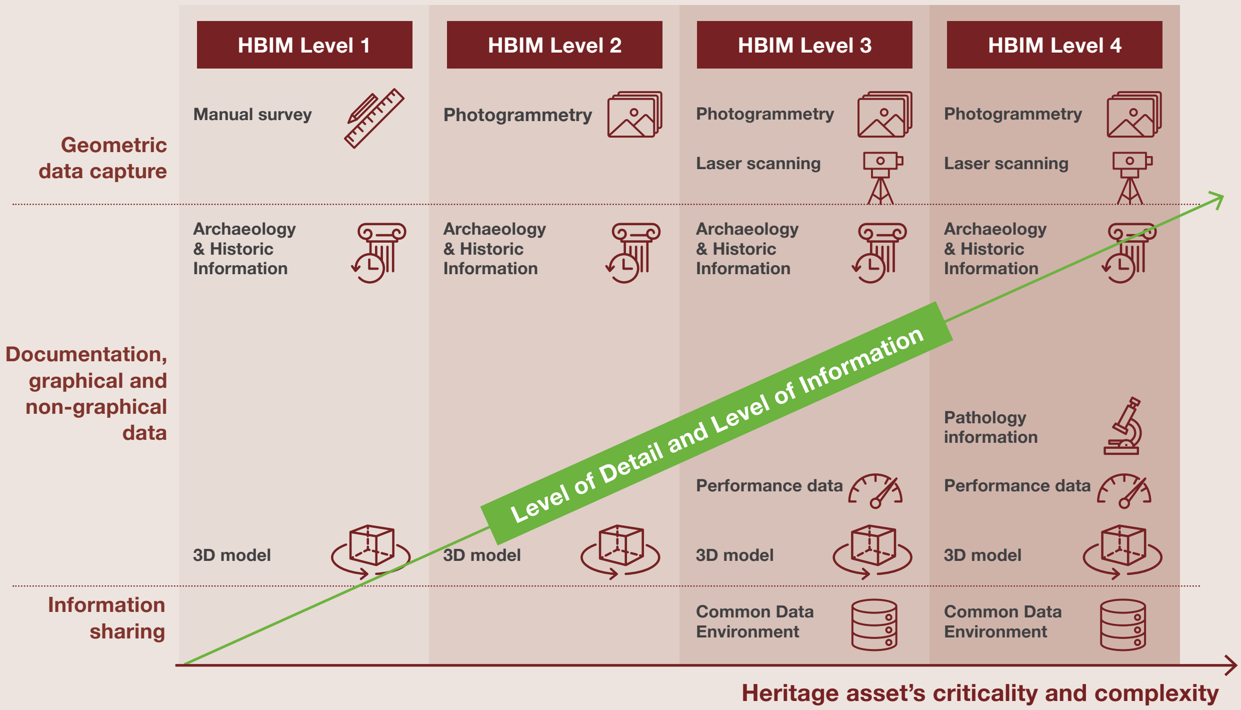


Figure 10 *HBIM levels and features*

HBIM Level 2 characteristics:

- It may either be built upon from the previous level or implemented outright.
- It features all technology used in Level 1 including historical and archaeological information. However, the main difference between the two levels is the development of a highly accurate 3D model that allows for more options for communication within the model regarding non-geometric data.
- The PCD set is most likely to be captured through photogrammetry, and the modelling process is done manually; complex objects are modelled separately from the base model.
- The level of detail is rated at a medium level as it can communicate the layout of the asset effectively but does not include time-consuming intricacies and complex sections.
- The heritage assets most suitable for Level 2 are similar to Level 1 but either may have planned maintenance that needs to be organised efficiently or the asset may provide enough funding to warrant HBIM Level 2.

HBIM Level 3 characteristics:

- It is the recommended level of implementation for heritage assets. Although the outright implementation of Level 3 is unlikely, building upon previous levels to achieve Level 3 is feasible.
- It contains all geometric and non-geometric information from previous levels and similar modelling processes of PCD.
- Laser scanning is more suitable within Level 3 as it is used for more complex heritage assets that require detailed PCD sets.
- A high level of detail for the BIM model is recommended to use the full potential of the laser scanned PCD.
- The most significant difference between Levels 3 and 2 is the establishment of a centralised CDE which drastically contributes toward collaboration among stakeholders.
- All files are within the selected format, and the HBIM model is the single source of information.
- The heritage assets suitable for Level 3 feature complex objects that require ongoing maintenance or are more iconic and thus could benefit from HBIM.

HBIM Level 4 characteristics:

- It is the highest level of HBIM implementation.
- It features advanced technology methods to capture information and innovative software to communicate information.
- A 3D model of the asset is produced using laser scanning or photogrammetry to create PCD.
- The produced model incorporates all information of the heritage asset and features a high level of detail and level of information, including intricate parametric objects.
- It uses investigation methods to capture information and data regarding the structural and material pathology of the building. All available information regarding the history and archaeology of the building is captured; if the information is unknown or missing, investigations to retrieve data are undertaken.
- All relevant performance data is captured regarding the building's performance and systems.
- All information and data retrieved are linked to a single CDE for all stakeholders to access and monitor the heritage asset.
- All operation and maintenance works are organised through the HBIM model.
- It should be utilised for iconic heritage assets that are cornerstones of communities and require new systems to manage the maintenance and preservation of the asset.

Collaborative BIM process

BACKGROUND

There has been quite a change in the information delivery process when digital technologies, such as Building Information Modelling, are now commonly adopted. It is now a collaborative process that involves many stakeholders, including clients, designers and project management contractors.

Although an ideal way of information management is to use a single platform to involve key stakeholders for a streamlined management process, this practice has complexity and difficulty given the number of participants that should be involved. The complexity and difficulty lead to resistance of change.

This case study aims to investigate the reasons leading to the resistance of change from the construction industry when implementing BIM and propose potential educational frameworks to ensure that the BIM team and contractors have the same level of understanding on information delivery in BIM to improve efficiency.

CASE STUDY OBJECTIVES

The specific objectives are to:

- Conduct a comprehensive review of potential reasons/barriers preventing the construction industry to change in order to identify the current and emerging trends and pitfalls with moving to BIM.
- Conduct a comprehensive review of good practices and education/training practices related to bridging the gap of understanding between the BIM team and downstream participants.
- Preliminarily examine the BIM related standards/plans from the BIM team of Sydney Opera House and compare them with best practices/guidelines from other major BIM players in the infrastructure sector. This provides an opportunity for all participants to understand the current implementation status of BIM across the country and different sectors.

RESULTS

1. Barriers that can prevent BIM adoption

A literature review has been conducted, through which 43 barriers for BIM adoption in AEC firms have been identified. These barriers are classified into four categories, namely social-organisational, financial, technical and contractual/legal, and 15 subcategories. Detailed information is shown in Table 2.

Among all the barriers that hinder the BIM diffusion, high adoption cost is the most frequently mentioned one in existing study. Social-organisational barriers, especially the reliance on traditional methods and lack of BIM understanding are also important barriers for effective BIM adoption. These include resistance to change, a lack of clients' demand, variant awareness of different stakeholders, stakeholders tending to avoid potential risks, lack of BIM personnel, and invisible benefits. In addition, lack of BIM standards, interoperability issues and compatibility issues are major technical concerns of the practitioners. Although national BIM standards are available in Australia, the standardisation of information is still a challenge.

Table 2 BIM adoption barriers:

Categories	Subcategories	Barriers for BIM adoption	Sources
Social-organisational	Reliance on traditional methods	Resistance to change/Adoption of traditional practices and standards/ Lack of trust in and apprehension towards new technology	Alreshidi et al. (2017); Anuar and Abidin (2015); Arayici et al. (2011); Babatunde et al. (2020); Bosch-Sijtsema et al. (2017); Carroll and McAuley (2017); Furry et al. (2017); Hong et al. (2019b); Hosseini, M. et al. (2016); Kouch et al. (2018); Li et al. (2019); Matarneh and Hamed (2017); Monozam et al. (2016); Rezgui et al. (2013)
		Lack of motivation	Alreshidi et al. (2017)
		Fragmented procurement paths/Poor collaboration among participants	Liu et al. (2015); Rezgui et al. (2013); Won et al. (2013)
		Unwilling to openly share data/Lack of data sharing mechanism	Alreshidi et al. (2017); Liu et al. (2015); Won et al. (2013)
	Lack of BIM understanding/ skills	Lack of BIM understanding	Alreshidi et al. (2017); Arayici et al. (2011); Babatunde et al. (2020); Matarneh and Hamed (2017)
		Lack of clients' awareness/demand; Lack of buy-in	Alreshidi et al. (2017); Babatunde et al. (2020); Bataw et al. (2014); Bosch-Sijtsema et al. (2017); Hosseini, M. et al. (2016); Li et al. (2019); Matarneh and Hamed (2017); Mellon and Kouider (2016); Monozam et al. (2016); Poirier et al. (2015); Reza Hosseini et al. (2018); Won et al. (2013)
		Lack of BIM training/knowledge/ personnel; Lack of subcontractors with BIM knowledge	Alreshidi et al. (2017); Arayici et al. (2011); Bryde et al. (2013); Liu et al. (2015); Matarneh and Hamed (2017); Won et al. (2013)
		BIM technologies learning curve	Liu et al. (2015); Won et al. (2013)

Categories	Subcategories	Barriers for BIM adoption	Sources
Social-organisational (cont).	Lack of BIM understanding/ skills (cont)	Variations in practitioners' skills or perceptions	Alreshidi et al. (2017); Anuar and Abidin (2015); Babatunde et al. (2020); Bataw et al. (2014); Bosch-Sijtsema et al. (2017); Carroll and McAuley (2017); Dainty et al. (2017); Furry et al. (2017); Hosseini, M. et al. (2016); Li et al. (2019); Mellon and Kouider (2016); Reza Hosseini et al. (2018)
		Avoiding potential risks/liability for mistakes	Alreshidi et al. (2017); Bataw et al. (2014); Charlson and Oduoza (2014); Hong et al. (2019a); Hong et al. (2019b); Kouch et al. (2018); Li et al. (2019); Monozam et al. (2016)
		Difficult to measure impacts of BIM/ Lack of vision of benefits	Babatunde et al. (2020); Bosch-Sijtsema et al. (2017); Hosseini, M. et al. (2016); Li et al. (2019); Reza Hosseini et al. (2018); Won et al. (2013)
	Culture/ Environment	Lack of enabling environment	Babatunde et al. (2020)
		Lack of senior management support	Babatunde et al. (2020); Bosch-Sijtsema et al. (2017); Liu et al. (2015)
		Lack of government support	Bataw et al. (2014); Joseph Garcia et al. (2018); Matarneh and Hamed (2017); Poirier et al. (2015)
		Scale of culture change required	Babatunde et al. (2020)
Financial	General cost	BIM adoption cost	Alreshidi et al. (2017); Anuar and Abidin (2015); Babatunde et al. (2020); Bataw et al. (2014); Dainty et al. (2017); Furry et al. (2017); Hochscheid and Halin (2018); Hong et al. (2019a); Hong et al. (2019b); Hosseini, M. et al. (2016); Kouch et al. (2018); Liu et al. (2015); Mellon and Kouider (2016); Monozam et al. (2016); Reza Hosseini et al. (2018); Rezgui et al. (2013); Sebastian (2010); Won et al. (2013)
		Lack of financial support	Bataw et al. (2014); Carroll and McAuley (2017); Dainty et al. (2017); Hosseini, M. et al. (2016); Li et al. (2019)
	Human related cost	BIM training cost	Alreshidi et al. (2017); Babatunde et al. (2020); Li et al. (2019); Liu et al. (2015)
		Expensive human-based services costs	Alreshidi et al. (2017)
	Hardware/ software cost	Limited budget and investment in ICT/ Cost of software/Cost of facility	Alreshidi et al. (2017); Arayici et al. (2011); Babatunde et al. (2020); Li et al. (2019); Liu et al. (2015); Rezgui et al. (2013)
	Others	Personal Indemnity Insurance is not covered	Alreshidi et al. (2017)

Categories	Subcategories	Barriers for BIM adoption	Sources
Technical	Lack of technologies and standards	Maturity of BIM-based technologies/ Inaccessibility to suitable technology and framework	Alreshidi et al. (2017); Babatunde et al. (2020)
		Lack of BIM standards	Babatunde et al. (2020); Carroll and McAuley (2017); Dainty et al. (2017); Hosseini, M. et al. (2016); Li et al. (2019); Liu et al. (2015); Monozam et al. (2016); Poirier et al. (2015); Won et al. (2013)
	Interoperability, collaboration and compatibility issues	Interoperability issues	Alreshidi et al. (2017); Arayici et al. (2011); Babatunde et al. (2020); Bosch-Sijtsema et al. (2017); Bryde et al. (2013); Joseph Garcia et al. (2018); Li et al. (2019); Monozam et al. (2016); Won et al. (2013)
		Compatibility issues between different IFC products	Bosch-Sijtsema et al. (2017); Furry et al. (2017); Hong et al. (2019b); Hosseini, M. et al. (2016); Hosseini, M.R. et al. (2016); Li et al. (2019); Monozam et al. (2016); Reza Hosseini et al. (2018); Rezgui et al. (2013)
		Inability of packages to exchange data	Bryde et al. (2013)
		Issues with existing BIM modelling and collaboration tools	Alreshidi et al. (2017)
		Lack of collaboration management tools	Won et al. (2013)
	Data volume and accessibility	Massive data inputs/outputs	Alreshidi et al. (2017)
		Massive data and limited data storage	Alreshidi et al. (2017)
		Limited accessibility and access rights/ access control	Alreshidi et al. (2017); Rezgui et al. (2013)
		Lack of data tracking, checking and versioning control mechanisms	Alreshidi et al. (2017)
		Difficulties coordinating large BIM models	Alreshidi et al. (2017)
	Others	Lack of notification mechanisms	Alreshidi et al. (2017)

Categories	Subcategories	Barriers for BIM adoption	Sources
Contractual/ Legal	Immature BIM contracts	Contractors benefit from confusion	Alreshidi et al. (2017)
		BIM contracts are not yet mature (roles, responsibilities of stakeholders)/ Lack of BIM-related aspects in current contracts	Alreshidi et al. (2017); Arayici et al. (2011); Liu et al. (2015); Rezgui et al. (2013)
		Failure to address BIM legal concerns in current contracts/Lack of legal considerations in existing BIM contracts	Alreshidi et al. (2017); Rezgui et al. (2013)
		Lack of legal framework for adopting collaborative BIM/Contracts need to accommodate changes in BIM collaborative environment	Alreshidi et al. (2017); Babatunde et al. (2020)
	Ownership of BIM model	BIM models ownership: intellectual property and copyright concerns	Alreshidi et al. (2017); Liu et al. (2015); Rezgui et al. (2013)
	Data related issues	Liability issues with wrong or incomplete data	Alreshidi et al. (2017); Rezgui et al. (2013)
		Data security risks	Rezgui et al. (2013); Won et al. (2013)
		Privacy issues (e.g., storage of business sensitive data)	Rezgui et al. (2013)
	Others	Personal Indemnity Insurance does not cover legal aspects of collaborative work	Alreshidi et al. (2017)

2. Good practices for BIM diffusion

Based on a literature review of best practices from Australia, Singapore and America, good practices in BIM implementation are identified and summarised. Compared to traditional project implementation, a BIM manager is a new and critical role for a BIM based project who is responsible for making a BIM execution/management plan, specifying team responsibility matrix, requiring BIM deliverables and deliverable schedules, controlling BIM modelling quality, and coordinating stakeholders. For BIM implementation, the following four aspects need to be considered:

- Roles and responsibilities of stakeholders. All three good practices that have been reviewed, including NATSPEC National BIM Guide, the National BIM Standard-United States and Singapore BIM Guide Version 2.0, have well defined the roles and responsibilities of stakeholders. While the NATSPEC National BIM Guide has covered a wide range of all roles; the National BIM Standard-United States® (NBIMS-US™) Version 3 also clearly indicates the interaction of various roles at different phases.
- BIM workflows. The National BIM Standard-United States® (NBIMS-US™) Version 3 has outlined the detailed BIM workflow. It provides detailed business processes during the life cycle of a BIM project, specifying stakeholders responsible for each process. In addition, how data is exchanged between stakeholders of different roles in each process is visualised in Figure 1 to Figure 29 of this standard. Another good practice shown in the Singapore BIM Guide Version 2.0 details workflows for design-build projects and design-bid-build projects separately.
- BIM deliverables and requirements. Table 5 to Table 29 of the National BIM Standard-United States® (NBIMS-US™) Version 3 details deliverables of each business process. It is recommended to read these in conjunction with Figure 1 to Figure 29 of this standard to see the exchange of the deliverables (e.g., who transfers which deliverable to whom). In addition, the Singapore BIM Guide Version 2.0 provides an example of deliverables at different stages in its Table 2 with sample models, their relation to 2D drawings and level of detail requirement. This might be more intuitive and easier to understand.
- Cross-disciplinary coordination. The three good practices provide totally different but equally important information in this aspect and could be used jointly. The Singapore BIM Guide Version 2.0 focuses on roles of stakeholders in the coordination flow, the National BIM Standard-United States® (NBIMS-US™) Version 3 gives an example for data management of the coordination, and the NATSPEC National BIM Guide sheds lights upon enablers of such coordination.

3. Digital engineering standards review

The Sydney Opera House (SOH) Digital Engineering Standard (DES) are a set of documents, defining the digital engineering standards to be used in the concept, design, construction, handover and ongoing management of the engineering assets and building structure at Sydney Opera House. There are four main SOH DES document sets: (1) Series 000 for Introduction & Preliminaries; (2) Series 100 for Contract Documents; (3) Series 200 for User Standards; and (4) Series 300 for Project Deliverables. In this case study report, we had reviewed two of them (i.e. SOH-DE.110 BIM Execution Plan and SOH-DE.210 Model Management Standard) which are the main BIM standards that successful contractors need to fulfil when working for and/or on behalf of SOH. The document of the BIM Execution Plan (BEP) describes the strategy, procedures and responsibilities relating to the use of BIM which forms part of the signed contract documents. The Model Management Standard (MMS) is the full comprehensive user reference document to ensure that the user is meeting the SOH DES and digital deliverables compliance requirements. All the concepts, strategies, principles, processes, and protocols defined in the BEP and MMS are well explained and aligned with the mainstream national and international standards as well such as ISO 19650, BIMForum LOD Specification, and NATSPEC BIM. However, the following two aspects we found could be further improved to increase the implementability of the SOH DES in practice:

(1) Asset Classification

OmniClass standard is currently used through the SOH DES for model discipline coding and BIM element classification. Based on the latest contents described in the MMS, project participants can easily find a detailed guide to correctly code BIM model disciplines, however, coding at the BIM element level is hard as the corresponding instructions is insufficient. For instance, the MMS only points out the requirement of adding "Omni Class Number" as one of the Shared Parameters in Revit but without providing any further descriptions or guidelines of how to fill an appropriate value. This might cause potential data inconsistency issues as different people may have different interpretations of the same OmniClass tables. Therefore, it would be useful to provide a unified Asset Classification list dedicated for SOH assets so that project participants could efficiently find correct OmniClass codes for any selected BIM elements or assets. There are two types of approaches which have the potential to address this issue. The first one is proposed from a management perspective. Instead of training project contractors to fill a correct "Omni Class Number" for each BIM element, project client (i.e. SOH DE team) will take the responsibility and fill all the required OmniClass codes internally. SOH has adopted this approach. From the SOH perspective, this approach is particularly beneficial as there are many small projects that are run by various contractors during the Decade of Renewal program. In order to mitigate the inconsistency related to the way that items are classified if various contractors are involved, in house classification is a streamlined process that has proven to be effective. The second approach will solve this issue through providing a unified SOH Asset Classification List (either in Spreadsheet or Revit Plugin). Project contractors will be able to efficiently find correct OmniClass codes for any selected BIM elements or assets without interpreting the OmniClass standard by themselves.

(2) Open BIM Workflow

The implementation of the current BEP and MMS heavily relies on Autodesk Revit which might limit the flexibility of contractor selection and BIM software utilisation. Given the fact that open BIM standards such as Industry Foundation Classes (IFC) and BIM Collaboration Format (BCF) have been widely used in the current construction industry, there is a need to develop a specific open BIM workflow as an alternative into the current SOH DES for BIM data sharing and exchange. With the support of the open BIM workflow as well as the existing Revit-driven approach, project contractors can have the freedom (not limited to Revit) to choose their preferred BIM tools such as Rhino, ArchiCAD, Tekla, and Allplan to create, view and update the 3D BIM models and deliver as-built asset information models as required without any data loss. Moreover, data compliance checking tools such as Solibri can be also leveraged to automate the BIM model checking process which could significantly accelerate the as-built model data handover.

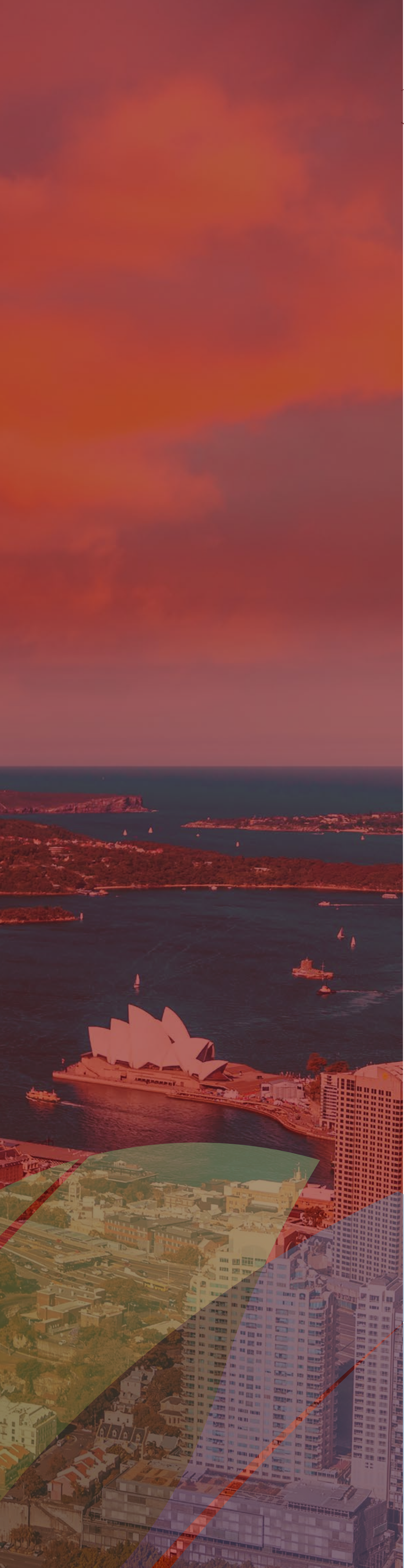
This particular open BIM workflow was attempted by SOH several years ago. At the time of investigation, the process was considered too complicated as it would have required geometrically editable models for delivery and required purchasing and training of various other software packages. In addition, given the high priority of the Decade of Renewal program at SOH, this process was not implemented. Given the advancements in recent IFC, the intent moving forward from the SOH perspective is to implement this strategy after the completion of the Decade of Renewal program.

Conclusion

This research project has established the use of lifecycle information, supported by innovative approaches, such as BIM and machine learning, for effective decision making.

Specifically, this project has demonstrated industry value at the following levels:

1. A machine learning algorithm has been developed to automatically assess pavement crack condition, which is often provided through expert's manual visual inspection.
2. Best-practice technologies and information management strategies for heritage assets and their unique preservation and restoration requirements. The exploratory work and guidance aims to form a more detailed asset information management strategy for heritage assets.
3. The reasons leading to the resistance of change from the construction industry when implementing BIM. Potential educational frameworks to ensure that the BIM team and contractors have the same level of understanding on information delivery in BIM to improve efficiency have also been proposed from the perspective of Sydney Opera House.



Moving forward

While the approaches and methods in this research project have been developed to address specific problems faced by the industry partners to the project, the results are useful for other industry agents who aim to incorporate digital engineering and advanced artificial intelligence techniques into their decision-making processes, and to develop training and educational materials to build capability to explore the benefits.

The project team will work closely with existing project partners to validate the benefits and impacts achieved from this project. We also welcome potential partners who intend to explore the benefits of advanced digital engineering and artificial intelligence approaches in their daily practices.

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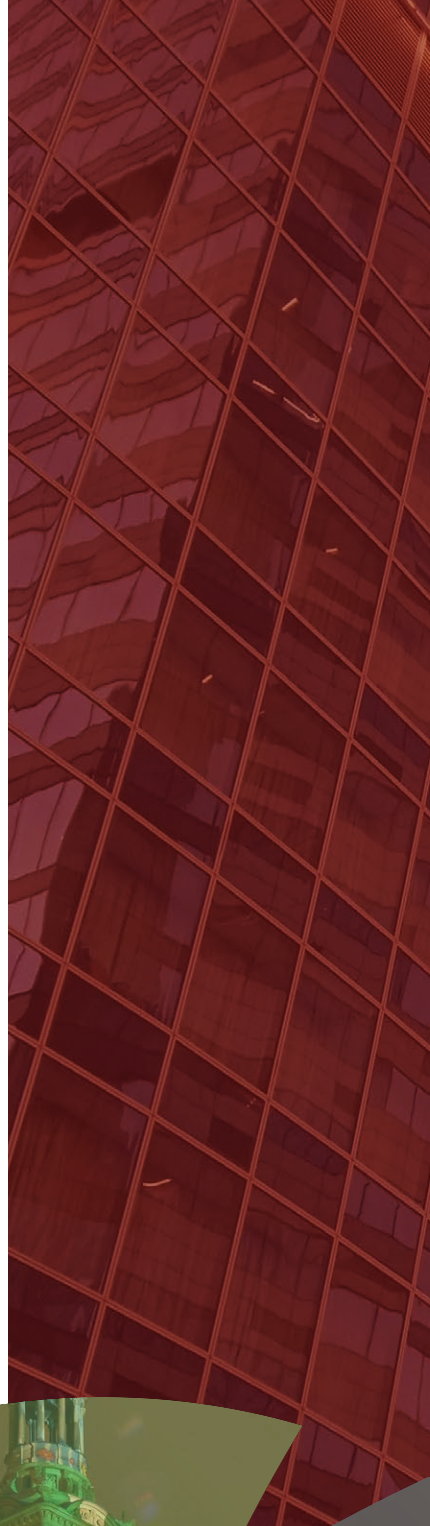

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