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Integration of TLS-derived Bridge Information Modeling (BrIM) with a Decision Support System (DSS) for digital twinning and asset management of bridge infrastructures

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ABSTRACT

In the current modern era of information and technology, the concept of Building Information Modeling (BIM), has made revolutionary changes in different aspects of engineering design, construction, monitoring, and management of infrastructure assets, especially bridges. In the field of bridge engineering, Bridge Information Modeling (BrIM), as a specific form of BIM, includes digital twinning of bridge assets associated with geometrical information and non-geometrical inspection data. BrIM has demonstrated tremendous potential in substituting traditional paper-based documentation and hand-written reports with digital bridge documentation/transformation, allowing professionals and managers to execute bridge management more efficiently and effectively. However, concerns remain about the quality of the acquired data in BrIM development, as well as lack of research on utilizing these information for remedial actions/decisions in a reliable Bridge Management System (BMS), which are mainly reliant on the knowledge and experience of the involved inspectors, or asset managers, and are susceptible to a certain degree of subjectivity. To address these concerns, this research paper presents a comprehensive methodology as an advanced asset management system that employs BrIM data to improve and facilitate the BMS. This innovative BMS is comprised of a precise Terrestrial Laser Scan (TLS)-derived BrIM as a qualitative digital replica of the existing bridge, incorporating geometrical and non-geometrical information of the bridge elements, and equipped with a requirement-driven framework in a redeveloped condition assessment model for priority ranking of bridge elements based on their health condition. In another step ahead, the proposed BMS integrates a Decision Support System (DSS) to score the feasible remedial strategies and provide more objective decisions for optimal budget allocation and remedial planning. This methodology was further implemented via a developed BrIM-oriented BMS plugin and validated through a real case study on the Werrington Bridge, a cable-stayed bridge in New South Wales, Australia. The finding of this research confirms the reliability of BrIM-oriented BMS implementation and the integration of proposed DSS for priority ranking of bridge elements that require more attention based on their structural importance and material vulnerability, as well as optimizing remedial actions in a practical way while preserving the bridge in a safe and healthy condition.

1. Introduction

Bridge infrastructures are among the vital component of the built environment and road network. Over time, during bridge operation and exposure to the environment and service loads, the health of infrastructure deteriorates. If the process of deterioration is not controlled or managed, a situation can arise where the infrastructure ceases to serve its purpose or becomes obsolete. In this case, the bridge infrastructure may be decommissioned, repurposed/degraded, or replaced with a new infrastructure. Therefore, negligence in proper maintenance and management or delayed action, particularly for bridge infrastructure, may result in high future expenditures, degraded assets, and, in the worst-case scenario, lead to catastrophes such as the Morandi bridge (Calvi et al., 2019) and Taiwan's Nanfang'ao bridge (Horgan, 2019) collapses. As the number, and age of these infrastructures increase, so does the need to monitor the health, management, and maintenance of these important structures. Just as bridges are an integral part of society, it is important that new technology is given consideration towards

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improving the way in which these infrastructures become inspected, managed, and maintained (Elfgren et al., 2007).

For many years, bridge management approaches and condition assessments have been based on long-established manual paperwork and information retained from on-site inspectors and engineers (Rashidi et al., 2020). These approaches have been primarily paper-based and significantly limit the ability to be readily transferred to asset managers or be referred after a few years. However, the development of Building Information Modeling (BIM) in recent years, has led to a transformation in the digitalization of structural assets and their information in form of a digital twin, which in the field of bridge engineering pertains to the Bridge Information Modeling (BrIM) (Kaewunruen et al., 2020; Perno et al., 2022; Semeraro et al., 2021). Chan et al. (2016) were among the researchers who emphasized that it is currently essential for bridge owners to make use of BrIM as a database to store various sources and types of information such as bridge drawings, inspection records, rehabilitation activities, condition state of elements, records of remote sensors, and history of decisions with a timestamp and reference. In general, BrIM is a shared database/platform, that often consists of the bridge geometrical 3D Computer-Aided Design (CAD) models, as digital representation of the physical characteristic of the bridge asset, as well as non-geometrical information as digital documentation such as visual inspection reports, damage locations and maintenance histories, remote sensors' records, diagnostic test results, element's material, and other specifications (Mohammadi et al., 2022; Wenner et al., 2021). With a BrIM, this information can then be widely shared/disseminated amongst the stakeholders involved, assisting bridge manager, and assessors, as a reference for their future decisions. Despite the fact that BrIM is an innovative method for storing varied information, two concerns remain in terms of: 1) creating an accurate digital representation and collecting remote and reliable information, 2) utilizing BrIM data for management purposes in a reliable Bridge Management System (BMS).

To address the first concern, BrIM development extracted from remote data collection was initiated as a reliable and qualitative concept in studies conducted by Lubowiecka et al. (2009), Tang and Akinci (2012), and over time, this concept has seen exponential growth in its application, and scope (Sacks et al., 2018; Mohammadi et al., 2022). In general, determining changes in geometry, detection of defects, and the overall condition assessment of bridges were carried out through visual inspections, which were reinforced by inspection procedure manuals and guidelines developed by roads and traffic authorities (Tfnsw, 2007). However, these inspections were prone to subjectivity, impacted by the experience and knowledge of the inspectors engaged, labour-intensive, time-consuming, and in most cases were not traceable (Riveiro and Lindenbergh, 2019). These inspections also require special tools and equipment, such as lifting units, scaffolding, or rope climbing, with its associated risks, to get access to areas that would otherwise be inaccessible. In recent years, in order to tackle this risk and ease the data capture process, emerging technologies such as Terrestrial Laser Scanning (TLS) and Unmanned Arial Vehicle (UAV) photogrammetry have been utilized, and have made a significant impact on remote data collection and qualitative inspection of the bridges (Dorafshan and Maguire, 2018; Mohammadi et al., 2021b; Mohammadi et al., 2021a). These technologies have eliminated the inefficiencies and risks of site inspections in favor of detailed office inspections based on high-quality data obtained. Although these technologies have the capability of remote data collection and inspection, each has strengths and weaknesses in terms of flexibility, geometrical accuracy, and data quality, which may need to be varied based on the requirements of a bridge project to the next (Mohammadi et al., 2021b). When compared to other technologies, TLS, being the ground-based and most prevalent form of laser scanning technology, delivers benefits through rapid and qualitative capture of an object's surface topography via the reflection of the emitted laser beams (Mohammadi et al., 2021b; Chen et al., 2019). In the process of scanning, a TLS captures and stores three-dimensional (3D) data points, namely the x, y, and z coordinates of object's points, all in a short time frame. Many thousands of these points, each one corresponding to a different location on the physical object, can be amassed to form a file named point cloud. This file may subsequently be utilized for a variety of applications, after post-processing and optimization, including bridge inspection and assessment (Fuchs et al., 2004; Tang et al., 2007; Chen, 2012; Mizoguchi et al., 2013; Teza et al., 2009; Kim et al., 2015; Conde-Carnero et al., 2016), and Bridge Information Model (BrIM) development (Barazzetti, 2016; Xiong et al., 2013; Mohammadi et al., 2022).

In terms of bridge inspection, Fuchs et al. (2004) were among the key researchers who employed a laser-based instrument for bridge assessments of several highway bridges in the United States of America in 2004. In their research study, they employed the former technology of laser scanning to measure the deflections of bridge girders under static loading. In a similar strategy, Tang et al. (2007) employed this approach to expedite the collection of bridge geometrical information, such as vertical clearance, which was required for assessing bridge functional efficacy as specified by the National Bridge Inventory (NBI) program developed by American transportation authorities. In a research study, Mizoguchi et al. (2013) proposed a practical approach for using TLS data in quantifying surface damages such as mass loss and scaling. They utilized this approach to calculate the depth and area of damages caused by freeze–thaw cycles on an ancient concrete bridge. Similar methodologies were also explored for different damage detections in studies by Kim et al. (2015) and Teza et al. (2009) for structural elements' damage quantification, however, research remains fairly lacking a comprehensive methodology for estimating the overall condition state of the bridge structure using these valuable data.

In respect to bridge assessment, Conde-Carnero et al. (2016) utilized the acquired TLS-based point cloud to create a Finite Element (FE) model of a pedestrian bridge and assess its load-bearing capability following additional upgrades. In an interdisciplinary bridge assessment, Pérez et al. (2018) combined TLS technology for detailed geometrical identification and Ground Penetration Radar (GPR) to determine composition of fillers and structurally examine/analyze an ancient Roman bridge. Despite significant research efforts that resulted in empirical testing of more efficient models, most TLS-based bridge inspections were not utilized to develop a management system.

In terms of BrIM development using TLS point cloud, known as TLS-derived BrIM, Tang et al. (2007), Hinks et al. (2013), Riveiro and Lindenbergh (2019), Mohammadi et al. (2022) proposed methodologies that have meaningfully improved the efficiency of automated data extraction, accelerated the creation of bridge 3D CAD models, and resulted in a better means of both recording detailed bridge information, as well as serving as a reliable source of information for future reference and decisions.

However, in response to the second concern, research remains relatively limited to the development of BrIMs, and current Bridge Management Systems (BMSs) as well as designed software rely on frameworks that lack an optimized management planning endorsed by a decision support system, which this process was originally vulnerable to subjectivity due to the varying experience and expertise of the engineers involved (Rashidi et al., 2016a; Li et al., 2021). Although there are several BMSs available on the market, the majority of them are inventory asset management platforms with insufficient and subjective procedures, resulting in limited decision-making and asset management outputs.

Therefore, this research paper provides a thorough methodology to not only use valuable benefits of having a detailed TLS-derived BrIM but also present an innovative BMS integrated with a multi-criteria Decision Support System (DSS), targeting a powerful bridge asset management system with more reliable bridge management decisions in remediation strategy planning using BrIM data. During this study, a redeveloped approach for calculating Priority Rating Condition Index (PRCI) of bridge elements is elaborated. This approach is then expanded to a DSS for optimizing major bridge maintenance plans within acceptable safety, functionality, and sustainability boundaries. This methodology is further implemented in a designed BMS plugin and validated using a real bridge case study, Werrington Bridge, a cable-stayed bridge in New South Wales, Australia.

2. Research methodology

With the growth in the number of bridge inventory worldwide, bridge monitoring, condition assessment and management have become increasingly essential and challenging. Although many BMSs have been developed to date, the most recent update is the approach of BrIM-oriented BMS (Saback de Freitas Bello et al., 2022; Nguyen et al., 2022; Shim et al., 2019). This approach utilizes a virtual bridge representation that includes lifetime and updated non-geometrical data, also known as the BrIM, that is linked to a management system, resulting in the digital transformation of structural assets to form a digital twin (Boyes and Watson, 2022). BrIM itself is often formed of a 3D geometrical representation of the bridge linked to non-geometrical data such as elements' condition states, maintenance records, monitoring data, and reports. As bridge condition constantly changes over time, it is necessary to update the BrIM to replicate the 'as-is' condition of its physical counterpart. Given the time and effort involved in updating the BrIM, amassing accurate and reliable information, can be a time-consuming task, especially if data collection is performed manually. Therein, this research study employs laser scanning as an efficient means of measuring the geometry within the bridges as well as reliable and accurate data for bridge condition assessment in a TLS-derived BrIM development. This information model is indeed a fundamental source in supplying proper inputs to any management system. Following this, a collaborative management system is introduced to utilize the advantages of the TLS-derived BrIM and provide better services for bridge maintenance and management planning. This system introduces a concept of element-based Priority Rating Condition Index (PRCI) combined with a DSS to not only bring additional holism to current condition assessment techniques, but also provide more objective decisions for remedial planning. The concept of employing this system/-methodology is then explored in the development of a BrIM-oriented BMS plugin. The workflow of this methodology is depicted in Fig. 1 and is divided into two main subsections: the first comprises an overview of TLS-derived BrIM development and the second is its incorporation with novel BMS workflow as the focus of this research study, which is detailed in the following sections. TLS-derived BrIM development is divided into two phases of CAD model creation, and data assignment, as outlined in another study of our research team conducted by Mohammadi et al. (2022). To further describe the entire process and demonstrate the reliability of the proposed methodology, and developed plugin, the research is extended to an actual bridge case study after TLSing the Werrington Bridge located in Penrith, New South Wales (NSW), Australia.

2.1. Integration of BrIM into BMS

Nowadays, bridge health assessments are determined using a long-established inspection manual report developed by road authorities worldwide (TfNSW, 2007; Fhwa, 2018; Ri-Ebw-Prüf, 2017; Chase et al., 2016).

During the progress that has been made in recent years, these reports have also been converted to electronic documents and are now stored in existing management systems. However, concerns remained on the quality of inspections and applicability of the acquired information in an effective bridge management system which requires reliable data for making reasonable and correct decisions to determine the best remediation strategy or budget allocation. Therefore, the proposed approach of TLS-derived BrIM integration into BMS can not only provide a unique solution for a quick, intelligent, and reliable bridge inspection over traditional methods, but it can also provide a rich database for management purposes. In another step ahead, the proposed BMS of this research is designed to be based on a requirement-driven framework in a redeveloped Priority Ranking Condition Index, PRCI, for evaluating bridge elements. This index is a supplement ranking system that incorporates not only the general condition state of bridge elements but also takes additional variables such as their structural importance, and material vulnerability into consideration. In addition, PRCI reduces the subjective nature of personal inspections in terms of safety and serviceability, while also improving the consistency of management decision and remedial actions for each element. As shown in Fig. 1, using this ranking system, bridge element types with greater PRCI will be given more attention in terms of bridge structural efficiency, and will be subjected to a risk assessment procedure in a decision-making system to evaluate the possible remedial actions and their costs. In general, management decisions are based on the experience of bridge managers or established rules of thumb achieved over the years. These decisions may also be prone to potential inaccuracy and lack adequate reliability or compulsion that may aggravate dilemmas related to funding and infrastructure needs. Therefore, bridge asset manager needs to get more reliable supports that can assist them in identifying suitable actions and strengthening their credibility with prospective stakeholders. Therein, this research study proposed the integration of a DSS, thereby evaluating the risks and criteria involved and then devising alternative remedial strategies and budget-based planning.

2.2. Designed BrIM-oriented BMS plugin

The designed BrIM-oriented BMS plugin of this research study, consists of three main layers of 3D CAD model generation, application development, and report compilation. The first layer is 3D CAD model generation of the bridge using the captured TLS point cloud and the proposed novel sliced based algorithm described in the study conducted by Mohammadi et al. (2022). Using this algorithm in Python language, the bridge point cloud is divided into several point cloud slices, which were then imported into Tekla Structures (Trimble Solutions Corporation, 2021) CAD software for 3D solid modelling using general plane fitting and extrusion techniques. The extracted bridge model is then segmented based on their element types and exported to an exchangeable 3D format such as Industry Foundation Class, IFC. The second layer, application development, consists of user interface design and the implementation of functional modules in Microsoft Visual Studio using Tekla open API (Application Programming Interface). These functional modules are meant to be completed based on expert user input for each bridge element before performing BMS assessment tasks in the evaluation module. The evaluation module is based on the redeveloped condition rating system and integrated DSS, which are explained in Section 3. This plugin is a cloud-based data storage system/platform that allows bridge users, inspectors, and managers to reach documents at various levels of access. In the last layer, report compilation, the output of the BMS plugin assessment is imported back into the Tekla Structures software and visually presented as well as a paper report produced. Fig. 2 illustrates the workflow of the BrIM-oriented BMS plugin.

3. Key points of novel BMS

The two key operations in the proposed BMS of this research study are based on a redeveloped condition rating system followed by a DSS evaluation, which is elaborated in this section.

3.1. Redevelopment of bridge condition assessment concept

The bridge condition or health index is a valuable means of determining a bridge's structural or functional health. This index is generally determined using the structural conditions of the bridge elements and the bridge service supplied, identifying the most deteriorated elements, and determining the necessary repairs in bridge remedial actions (Chase

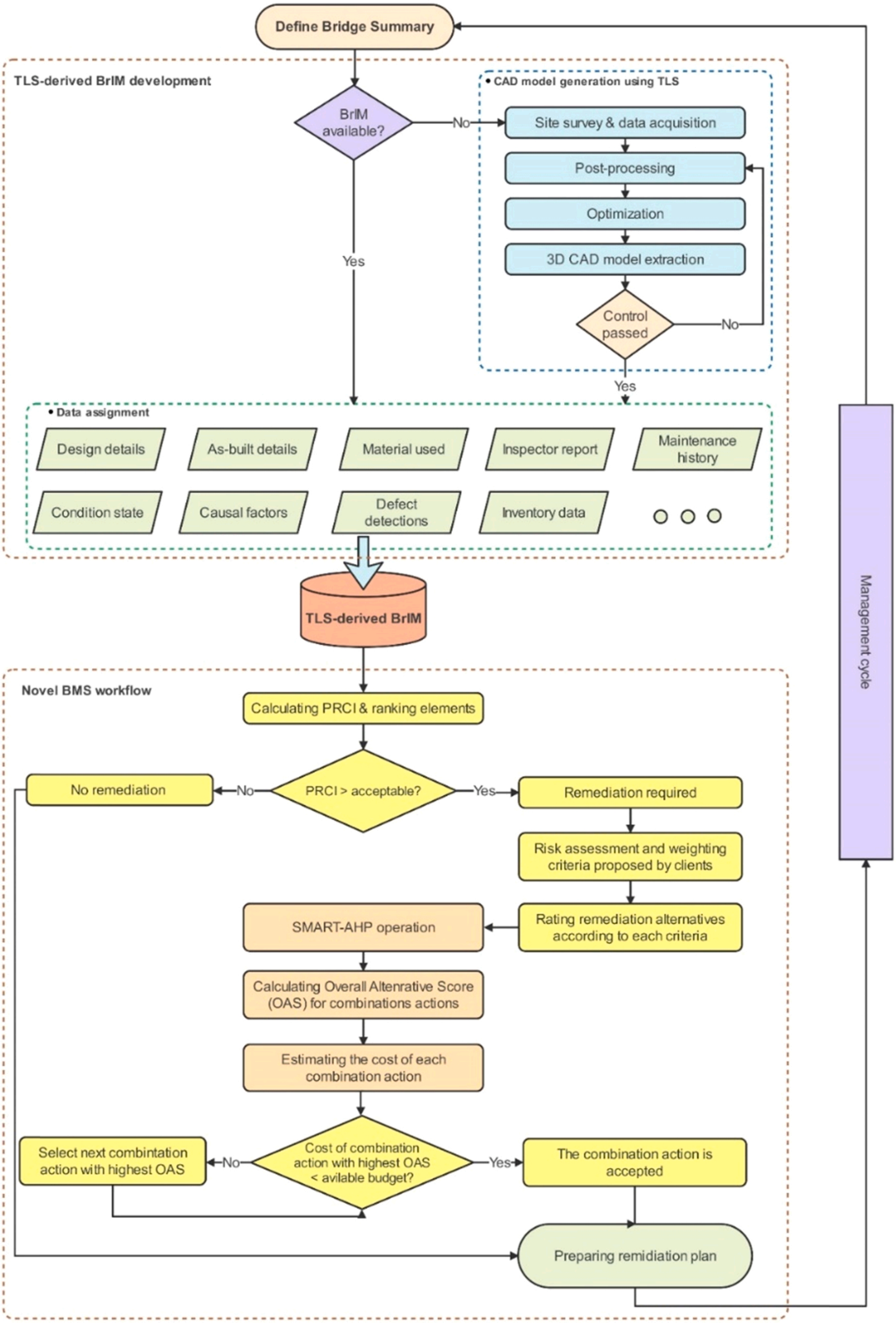


Fig. 1. TLS-derived BrIM and BMS integration workflow.

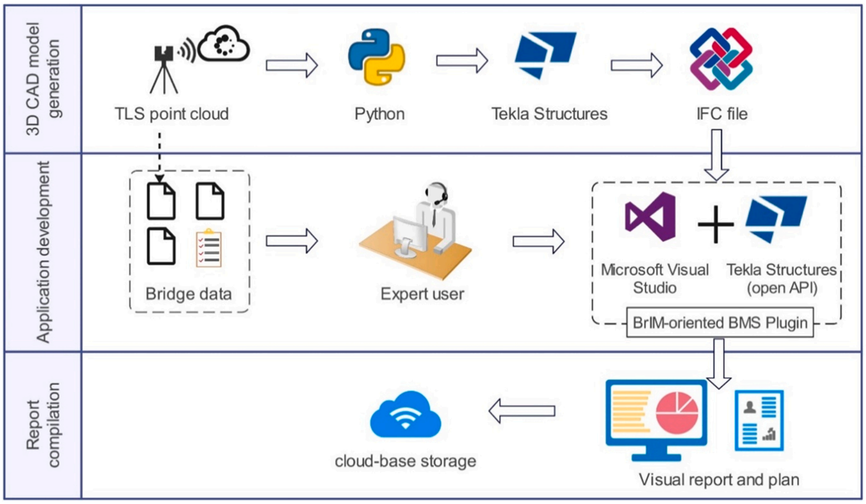


Fig. 2. The workflow of BMS plugin.

et al., 2016). To be consistent with current trends in both Australian and global bridge inspection standards, as well as bridge inspection procedure manuals established by road authorities such as Transport for NSW (TfNSW) (TfNSW, 2007), the proposed Priority Ranking Condition Index (PRCI) of this research study attempts to use not only the four general qualitative Condition Indices (CI), provided in Table 1, but also to tackle the subjective nature of this process and reduce the uncertainty using a set of weighting factors for ranking bridge elements. This approach not only provides a detailed picture of how degradation spreads across bridge elements, but it also serves as an effective index to assist bridge engineers to prioritize maintenance and planning rehabilitation for bridge assets.

In this research study, three factors are considered to be used in the procedure for evaluating the influence of technical indicators and determining a much more reliable bridge maintenance plan. Therefore, the element weighting factor (W_e) is defined, consisting of element Importance Factor (IF_e), multiplying by element Material Vulnerability (MV_e), and Casual Factor (CF_e) scaled by their overall weighted average. The $PRCI_e$ incorporates all the factors/parameters mentioned that influence structural performance and is calculated by following formula:

$$PRCI_e = \frac{CI_e}{\overline{CI}} \times W_e \tag{1}$$

where CI_e is the element condition state and $\overline{CI}$ is the overall bridge health index, which can be calculated using Eq. (2) (Jiang and Rens, 2010) and 3, respectively. Eq. (4) also computes the weighting factor, W_e, where e is the number of elements, and $\overline{IF}, \overline{MV}, \overline{CF}$are their overall weighted averages.

$$CI_e = \frac{\sum_i (q_i \times CI_i)}{\sum_i q_i} \tag{2}$$

$$\overline{CI} = \frac{\sum_e (CI_e \times IF_e \times MV_e \times CF_e)}{\sum_e IF_e \times MV_e \times CF_e} \tag{3}$$

where i is defined as the number of condition states, q_i is the quantity of the elements in ith condition state, and CI_i is the condition state index corresponding to the ith condition state.

$$W_e = \frac{IF_e}{\overline{IF}} \times \frac{MV_e}{\overline{MV}} \times \frac{CF_e}{\overline{CF}} \tag{4}$$

As determining the weighting factor and its parameters often requires special knowledge and field testing, particularly for material vulnerability and structural assessments, the inspector can rely on the proposed systematic approach of this research investigated through a semi-structured field interview/survey with experts and engineers in the field of bridge engineering and management. In the following subsections, these factors are elaborated.

3.1.1. *Importance Factor (IF)*

As previously indicated, the current condition state evaluation alone may cause some distortion in evaluating the overall bridge health condition. A minor element with worse condition may unreasonably raise the values and jeopardize the judgments (Dabous and Alkass, 2010; Gorji Azandariani et al., 2022). Therefore, this problem is resolved using the quantified element's structural Importance Factor (IF), which is not dependent on the current condition of bridge components. Based on the above-mentioned expert survey, the bridge components are classified into four categories of primary, secondary, tertiary, and other elements. As shown in Table 2, the higher the value, the greater the influence of the elements on the load-bearing behavior and safety of the bridge structure.

3.1.2. *Material Vulnerability (MV)*

Understanding the vulnerability of various materials can contribute to the durability of the elements under varying hazards throughout time. Although this parameter deserves comprehensive research for various

Table 1
General qualitative conduction indices (TfNSW, 2007).

CI	Descriptions
1	The element shows no deterioration. As-new condition or defects has no significant structural and functional effects.
2	Minor defects and early signs of deterioration with no reduction in element functionality.
3	Moderate defects and deterioration with some loss of expected functionality.
4	Severe defects with significant loss of functionality or element on the verge of failure.

Table 2
Structural Importance Factor (IF) (Dabous and Alkass, 2010).

IF	Bridge elements
1	Other elements; including but not limited to barriers, kerbs, footway, joints
2	Tertiary elements; including but not limited to foundation, abutment, wingwall
3	Secondary elements; including but not limited to deck, bearings, cables
4	Primary elements; including but not limited to beams, girders, piers, pylons

hazards, especially for bridge elements, in general an element made of steel is more prone to deterioration than a precast reinforced concrete element in terms of durability in a harsh environmental condition. Following the studies conducted by Valenzuela et al. (2010), as well as validating the expert surveys conducted, Table 3 shows the vulnerability of common materials used in bridge construction.

3.1.3. *Casual Factors (CF) and calibration*

Over time, as the infrastructure used, and is exposed to loading and environmental mechanisms, the health of bridge and its components deteriorates. If this process of deterioration is not well managed, the situation can arise where the bridge ceases to serve its purpose. Besides pre-existing factors, such as design and construction, several post-existing factors such as the environment where the bridge is located, the length of time the bridge has been in service (age), the functional performance that the bridge supports (road type), and the quality of inspection can all have an impact on the bridge's structural efficacy. Although these factors may be comparable for a bridge and its elements, the bridge elements may have different experiences in some circumstances. A bridge element can be upgraded over time, or it can be subjected to harsher environment than others. These factors can subsequently be used to evaluate overall bridge priority rankings when combined with overall functional efficiency factors, political considerations, and other relevant variables. Table 4 lists four categories of these factors, each of which is introduced by certain terms introduced in the following paragraphs.

Environmental aggression factor includes but is not limited to the natural environmental mechanisms that trigger chemical or physical deterioration to structural elements (Rashidi et al., 2016a). The level of these damages and the time frame for paying them off may vary depending on the severity of the environmental aggression. Sometimes a trace of the aggression or damage might be imperceptible at times, requiring a lab test to identify. Climate change, air, soil, or water pollution, chemical reactions, and human causes are all instances that may be classified at different levels and affect the overall structure's remaining lifetime (Byun et al., 2021). Moreover, other deterioration triggers, such as fatigue induced by repeated load applied to a structural element over the course of a bridge's lifetime, can promote cracks and fracture expansions. Therefore, the age factor and Annual Average Daily Traffic (AADT) associated with road type, as well as the road importance in network are generally recognized as key considerations not only for bridge design but also for evaluating element durability and bridge remaining lifetime. Besides, bridge inspection and its frequency are critical factors that must not be neglected. In this regard, four different levels of bridge inspection including initial, routine, detailed, and special inspection are defined in this research study. Initial inspection refers to the first inventory inspection following construction for data-driven preparation; however, routine inspection is typically focused on visual observations for general condition assessments. Aside from on-site visual observation, detailed inspection reinforced with non-destructive testing, and special inspection is supplemented with additional structural analysis when a serious incident occurs. It is worth noting that, regardless of the level of inspection, TLS application presented in this research study may be utilized for all different levels of inspection.

Following the implementation of the research studies conducted by Valenzuela et al. (2010), Rashidi and Gibson (2011), the CF index is calibrated using the results of the aforementioned survey of bridge engineers specialists rating the importance intensity of the casual factors. This rating process was based on the Saaty's nine relative importance scales and development of a pairwise matrix (Saaty, 1990), part of the Analytical Hierarchy Model (AHM), provided in our research team study conducted by Rashidi et al. (Rashidi and Gibson, 2011; Rashidi et al., 2016a), which is not the main concern of this study. Based on the rating process and the importance scales, the mathematical formulation for predicting the CF was developed as presented in Eq. (5).

$$CF_e = 0.12EA + 0.41A + 0.11R + 0.36I \qquad (5)$$

Table 3
Material Vulnerability (MV) (Valenzuela et al., 2010).

MV	Element Material
1	Precast concrete, non-structural elements
2	Reinforced concrete
3	Steel, iron, and other materials
4	Timber

Table 4
Causal Factor (CF) index (Rashidi and Gibson, 2011).

CF	Causal factors			
	Environmental Aggression (EA)	**Age factor (A)**	**Road type & loading (R)**	**Inspection level (I)**
1	Mild	Recently built (0–25 years)	Minor ($AADT \leq 150$)	Initial
2	Moderate	New (25–50 years)	Local access ($150 < AADT \leq 1000$)	Routine
3	Harsh	Old (50–75 years)	Collectors ($1000 < AADT \leq 3000$)	Detailed
4	Very Harsh	Very old (75–100 years)	Arterials ($AADT > 3000$)	Special

3.2. *Integration of a Decision Support System (DSS)*

Multi-criteria decision-making approaches are among the most robust and reliable analytic systems that have the potential to be integrated into a BrIM-oriented BMS. These approaches frequently use a qualitative relative comparison, to provide a systematic mechanism for weighting the multiple criteria, such as several risks involved, to evaluate and rank feasible alternatives (Wang et al., 2008; Grabot and Letouzey, 2000). In this regard, the Simple Multi-Attribute Rating Technique (SMART) and the Analytical Hierarchy Process (AHP) are two approaches that are widely utilized in many aspects of engineering and have the potential to be integrated into bridge infrastructure management (Abu Dabous and Alkass, 2008; Abu Dabous and Alkass, 2010; Rashidi et al., 2018). In this research study, a reasonable balance has been made between the simplicity of SMART and complexity of the AHP. In this case, a combined method of AHP-SMART with the capability of AHP's pairwise comparison of criteria and SMART's cardinal rating of each alternative has been utilized. Using this combined method, the limitation of restarting all calculations after adding a new alternative has been eliminated. During this process, bridge elements with the highest PRCI scores, outlined in Section 3.1, are subjected to AHP-SMART analysis after a risk assessment to evaluate the possible remedial alternatives.

Through the AHP-SMART process, the problem is subdivided into a hierarchy which includes three main levels of an overall goal, a group of alternatives for accomplishing the goal, and a set of criteria that tie the alternatives to the goal. In general, a criterion may not to be equally defined throughout this process, and thus may be graded/weighted based on several aspects of importance in terms of bridge engineering, management, and clients' constraints (Abu Dabous and Alkass, 2008). These weights can vary between projects and must be established by the individual involved in decision-making using the relative pairwise comparison embedded in Saaty's AHP method (Saaty, 1990). Moreover, alternative selection, which in the case of bridge rehabilitation refers to remediation alternatives/actions, entails a case-by-case risk assessment of alternatives and is tied to their associated course of actions. Therefore, bridge maintenance planners require to establish a balance between the relevance of the project's criteria and feasible alternatives.

3.2.1. *Criteria, remedial strategies, and budget optimization*

The primary concept of employing criteria is to evaluate the performance of each alternative in relation to the main goal based on a numerical scale. In the case of bridge rehabilitation, these criteria can be bounded into inclusion of subjective constraints such as functionality, sustainability, and reliability of the structural elements. In this case, the functionality can be extended through the operational efficiency of the elements that can affect the service life of the bridge, or the level of maintenance necessary to avoid the closure of a strategic route. However, the sustainability refers to the extension of such a service beyond having an effective work operation with a reasonable cost. Besides, element's reliability or safety depends on structural compliance with the applicable standards while causing less damage to the infrastructure and improving the structural capacity in return.

The majority of real-world decisions involve a combination of alternatives, and solutions out of various possible choices which require a careful evaluation of their pros and cons, the costs involved in making each choice, and the relative benefits (or disadvantages) of each option. Therefore, in terms of bridge rehabilitation, a range of satisfaction alternatives or remedial strategies has to be implemented to make it more feasible to ensure the functional, rational, effective and safe environment for people to travel across the bridges. In this regard, a potential remedial strategy can be classified into three levels (i) major alternatives, (ii) intermediate alternatives, and (iii) sub-alternatives. Major alternatives refer to the fundamental operational functions (including regular maintenance, minor rehabilitation, major rehabilitation, and replacement of the bridge elements), intermediate and sub-alternatives may refer to supplementary (including sub-structure redesign or specific engineering services) or provisional actions. The provisional actions of the sub-alternatives can be evaluated based on a fit to purpose classification after the fundamental/major alternatives have been carried out and endorsed in the form of a technical specification framework. This framework acts as a basis to evaluate various structural problems that

(a) Navigation map view of the Werrington Bridge

(b) Bridge view in 2021

Fig. 3. Werrington Bridge case study.

may arise or can be found in bridges of different types, as detailed in research studies conducted by Rashidi et al., (2016b, 2017, 2021), and Byun et al. (2021).

Road authorities across the world are dealing with an increasing number of deficient bridges, while their budgets for maintenance are generally limited, making necessary greater investigation and detailed risk assessment. In this respect, identifying vulnerable bridge elements, and providing a reliable maintenance plan with a number of prioritized alternatives can allow for not only a better knowledge of the bridge condition but also budget optimization and prioritization to preserve bridge safety in a secure state.

4. Werrington bridge case study

In order to further evaluate and demonstrate the procedures discussed, a real case study was conducted to collect the point cloud of a bridge named Werrington bridge which links the north and south campuses of the Western Sydney University (WSU), Werrington campus, built in 1992. The bridge, shown in Fig. 3, serves as a passageway for motor vehicles and pedestrians across the Great Western Highway, in Werrington, west of Sydney, Australia.

The Werrington bridge is an award-winning architectural structure with an asymmetric cable-stayed system designed out of an A-frame steel pylon with two legs and a composite deck with a reinforced concrete slab and an underlying steel frame. The composite deck is supported by two abutment walls, the pylon's beam, and a set of eight stay cables connected to the pylon's top end. In this research study, Werrington bridge case study is defined as a part of an asset management project for development of a TLS-derived BrIM, as well as assigning and assessing the soundness of the proposed methodology and implementing the designed BrIM-oriented BMS plugin for future bridge maintenance and management planning.

4.1. TLS survey and CAD model extraction

The scanning of the Werrington Bridge took place using Z + F IMAGER 5016 terrestrial laser scanner, shown in Fig. 4, following an initial site survey and investigation to identify the appropriate scan positions and parameters for the scan day strategy plan. Following that, the acquired data points from multiple scan positions have undergone filtration, registration, and colorization processes using the Z + F Laser Control V9 software (ZOLLER + FRÖHLICH GMBH, 2019).

The outcome of these procedures was an optimized point cloud with around 525 million discrete points, requiring approximately 15 GB of computer storage space, shown in Fig. 5(a). In the following, using the approaches presented by Mohammadi et al. (2021b), the quality of the point cloud data was checked with the as-designed drawings and as-is measurements conducted on different bridge elements that showed a millimeter-level of relative geometrical accuracy for the captured Werrington bridge point cloud. In the next step, the automatic slice-based algorithm introduced by Mohammadi et al. (2022), was utilized to generate a CAD model extraction of the bridge. Using this algorithm, the bridge point cloud is divided into several point cloud slices, which were then imported into Tekla Structures (Trimble Solutions Corporation, 2021) CAD software for 3D solid modelling using general plane fitting and extrusion techniques. Details of the Werrington bridge 3D CAD model extraction is beyond the scope of this paper, and are reported thoroughly in a research study by Mohammadi et al. (2022). The Werrington bridge CAD model is illustrated in Fig. 5(b).

Fig. 4. Werrington bridge data acquisition via TLS.

4.2. Werrington BrIM development

In this stage as illustrated in Fig. 2, the extracted 3D CAD model (IFC model) serves as the core of the BrIM, and different non-geometrical information, such as the parameters described in Section 3, were allocated to the bridge and its elements to create an information model of the Werrington Bridge. It is worth noting that data assignment was performed in the designed plugin, after a thorough review of the bridge, employing either the clash detections algorithm (Trimble Solutions Corporation, 2021; Javidan and Kim, 2022; Dorafshan and Azari, 2020) or off-site measurements and observations using TLS-based data, or existing reports from an expert engineer. The clash detection and progress tracking algorithms enable bridge engineers to discover changes in the bridge model or TLSed data over time, and the results could be a reliable source of information for bridge assessment at different levels of inspection. For instance, considering the concrete bridge deck of the bridge as the reference, the deviation of the 3D CAD model and point cloud was analyzed using Tekla Structures' built-in clash detection algorithm, resulting in the vertical deformation of the bridge illustrated by color counters in Fig. 6(a). In the case of the Werrington Bridge, the designed BrIM-oriented BMS plugin was then utilized to assign these sorts of engineering team's TLS data assessments and existing manual inspection reports to support digital transformation (digital twinning) of the bridge as a record. Overall distribution of allocated data into various bridge element types is shown in Table 5 and illustrated in Fig. 6(b). In this regard, the element codes, descriptions, units, and condition state interpretations were considered based on the Australian bridge inspection procedure manual developed by Transport for NSW (TfNSW, 2007).

In this procedure manual, the units rely on the exposed surface area or the number of exposed elements. The elements condition index, CI_e, was derived using Eq. 2, and the IF_e and MV_e were specified using their element codes, respectively. Moreover, the CF_e was defined based on previous maintenance records, exposed environmental condition, and level of inspection performed, as this factor was identical to all elements of this case study.

5. Result of BMS plugin Implementation

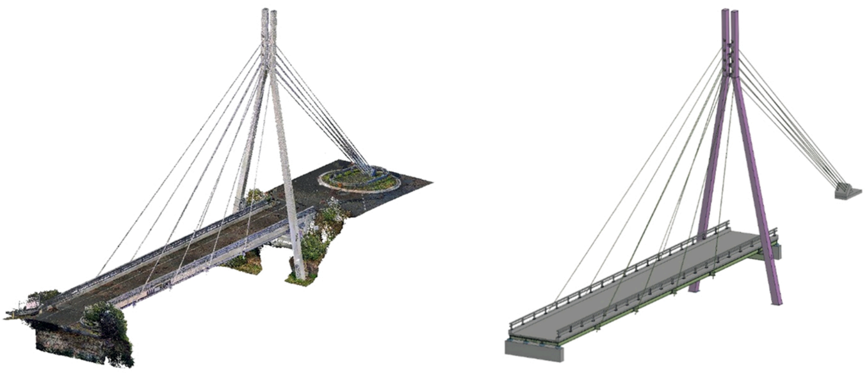
In this section, in order to further investigate the applicability of the proposed BrIM-oriented BMS plugin and DSS integration, the procedures from priority ranking of elements to rehabilitation strategy planning of the Werrington bridge are described.

5.1. PRCI-based priority ranking

In the case of the Werrington Bridge, the priority ranking of element types was carried out while calculating the PRCI. Table 6 demonstrates the element types in descending order of PRCI. As indicated in Table 6, the steel beams, bearing pads, and steel cables have the greatest PRCI among all other types of bridge elements, with 2.60, 2.00, and 1.80, respectively. Hence, those elements require specific attention in terms of budget allocation and remedial actions.

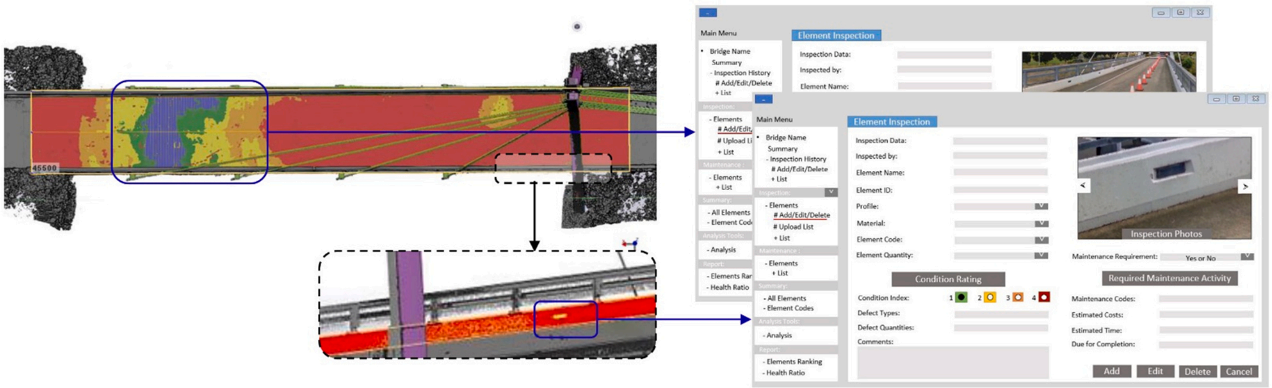
5.2. Scoring the remedial alternatives and budget-based prioritization

Following the priority ranking of element types, the SMART-AHP

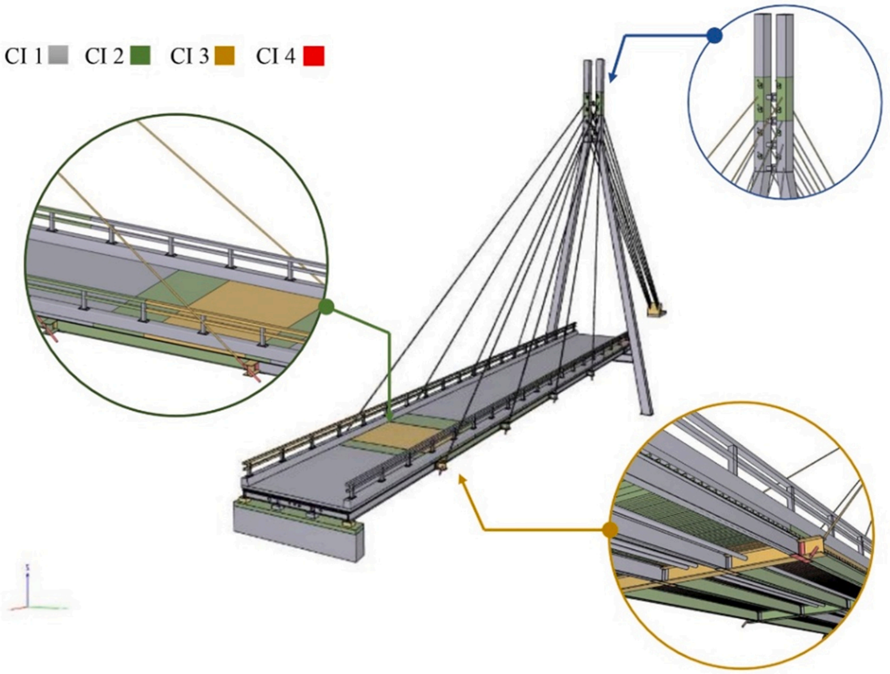


(a) Optimized point cloud (b) Extracted 3D CAD model

Fig. 5. Werrington bridge point cloud and CAD model.



(a) Clash detection and data assignment into BrIM-oriented BMS plugin



(b) CI of individual bridge elements

Fig. 6. Werrington Bridge digital transformation.

Table 5
Distribution of allocated data for various bridge element types.

No.	Element code (TfNSW, 2007)	Element description (TfNSW, 2007)	Total quantity, q	Unit	Estimated quantity in each condition index, CI				CI_e	IF_e	MV_e	CF_e			
					1	2	3	4				EA	A	R	I
1	SBGI	Steel Beam/Girder	332	m^2	270	48	14	0	1.23	4	3	1	2	1	2
2	SCBT	Steel Cables	16	ea	10	4	2	0	1.50	3	3	1	2	1	2
3	SPIR	Steel Pier (Pylon)	198	m^2	193	5	0	0	1.03	4	3	1	2	1	2
4	SCOD	Steel Corrugated Deck	285	m^2	243	18	24	0	1.23	3	3	1	2	1	2
5	SCGP	Steel Connection Gusset Plates	26	m^2	18	3.5	4	0.5	1.50	3	3	1	2	1	2
6	CDSL	Concrete Deck Slab	290	m^2	243	18	24	5	1.28	3	2	1	2	1	2
7	CABW	Concrete Abutment	81	m^2	67.7	5	3.8	4.5	1.32	2	2	1	2	1	2
8	RCON	Concrete Railing	92	m	82	0	5	5	1.27	1	1	1	2	1	2
9	RMET	Metal Railing	92	m	45	25	12	10	1.86	1	1	1	2	1	2
10	JASS	Assembly Joint/Seal	12	m	4	0	0	4	1.67	1	1	1	2	1	2
11	BELA	Elastomeric Bearing Pad	12	ea	8	0	4	0	1.67	3	3	1	2	1	2
12	WY	Waterway	5	ea	5	0	0	0	1.00	1	1	1	2	1	2
Weighted Average									1.38	2.83	2.66	1.77			

Table 6
PRCI-based ranking of Werrington bridge element types.

No.	Element Code (TfNSW, 2007)	Element description (TfNSW, 2007)	CI_e	$CI_e/\overline{CI}$	$IF_e/\overline{IF}$	$MV_e/\overline{MV}$	$CF_e/\overline{CF}$	$PRCI_e$
1	SBGI	Steel Beam/Girder	1.23	0.89	1.65	1.77	1	2.60
11	BELA	Elastomeric Bearing Pad	1.67	1.21	1.24	1.33	1	2.00
2	SCBT	Steel Cables	1.50	1.09	1.24	1.33	1	1.80
5	SCGP	Steel Connection Gusset Plates	1.50	1.09	1.24	1.33	1	1.80
3	SPIR	Steel Pier (Pylon)	1.03	0.74	1.65	1.33	1	1.62
4	SCOD	Steel Corrugated Deck	1.23	0.89	1.06	1.33	1	1.25
6	CDSL	Concrete Deck Slab	1.28	0.93	1.24	0.89	1	1.03
7	CABW	Concrete Abutment	1.32	0.96	0.82	0.89	1	0.70
9	RMET	Metal Railing	1.86	1.35	0.41	0.45	1	0.25
10	JASS	Assembly Joint/Seal	1.67	1.21	0.41	0.45	1	0.22
8	RCON	Concrete Railing	1.27	0.92	0.41	0.45	1	0.17
12	WY	Waterway	1.00	0.73	0.41	0.45	1	0.13

was employed to evaluate the major remediation alternatives/strategies for each bridge element type. Considering the goal of Werrington Bridge rehabilitation, these alternatives were considered to be evaluated using a set of criteria, based on client preferences, which were defined and weighted to maximize safety and service life while minimizing traffic disruption and costs. Throughout this procedure, as explained in Section 3.2, these constraints/criteria were articulated quantitatively by the experts in this area using Saaty's nine relative importance scales (Saaty, 1990). In this respect, Table 7 displays the generated pairwise comparison matrix, which includes the main client criteria identified as well as the relative importance scales of pairs assessed by experts' judgments in relation to the overall bridge rehabilitation objective. In the case of Werrington bridge, this matrix shows the strong importance of safety in the rehabilitation process, over the service life criteria. Moreover, Fig. 7 depicts the procedure's hierarchical structure used.

Following this procedure, the criterion weights are determined, as shown in Table 8, which reveals that safety and cost have the greatest contributions. Moreover, the consistency check resulted in a Consistency Ratio (CR) of 0.0043, which is less than 0.1, indicating that the completed judgement is consistent. With respect to each criterion, expert judgments were also used to compare the major alternatives for each element type using Saaty's nine relative importance scales (Saaty, 1990). This evaluation needs to be conducted for the element types with the highest PRCI, generally for elements with greater than two scores, which may be varied based on client preferences between projects. For the Werrington bridge, two element types of steel beam/girder, SBGI, and elastomeric bearing pad, BELA, were candidates to be examined. Table 8 shows the score of the major remedial alternatives for these two element types. During this procedure, the Overall Alternative Score (OAS) of each activity for specific element types was determined to be utilized for optimized remediation planning after the budget allocation.

Table 7
Pairwise matrix of main criteria in respect to Werrington Bridge remediation.

	Service Life	Safety	Cost	Traffic disruption
Service Life	1	1/5	1/3	3
Safety	5	1	3	7
Cost	3	1/3	1	5
Traffic disruption	1/3	1/7	1/5	1

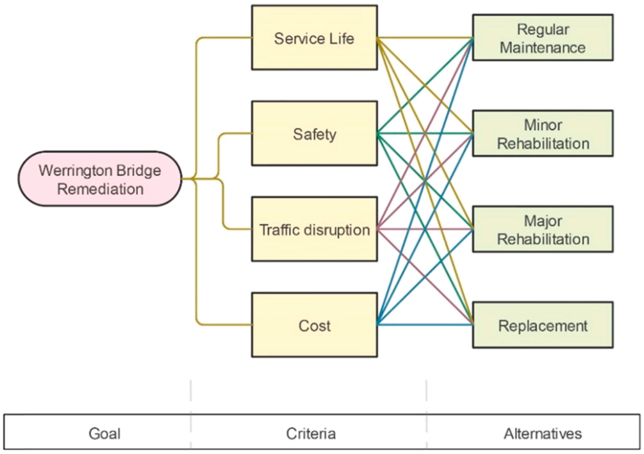


Fig. 7. Three-level hierarchical framework for remedial planning of Werrington Bridge.

Table 8
Scoring the major remedial alternatives for element types with the highest PRCI.

Criteria	Criteria Weights (%)	SBGI, Major remedial alternatives				BELA, Major remedial alternatives			
		Regular Maintenance	Minor Rehab.	Major Rehab.	Repl.	Regular Maintenance	Minor Rehab.	Major Rehab.	Repl.
Service Life	12.19	1	2	5	5	1	1	1	6
Safety	55.79	1	2	3	5	1	2	2	5
Cost	26.33	3	4	5	2	2	4	4	3
Traffic Disruption	5.69	5	5	5	2	5	5	5	2
OAS		175.4	269.7	388.4	403.9	149.1	257.5	257.5	442.5

As shown in Table 8, OAS for SBGI and BELA replacement were higher than for other activities; nevertheless, for the BELA, similar scores were obtained for minor and major rehabilitation, indicating that BELA major or minor rehabilitation was in same level of effectiveness in terms of Werrington bridge rehabilitation.

Following that, budget optimization was accomplished by establishing possible action combinations, calculating the cumulative OAS and actual cost of each combination, and then comparing it to the annual bridge budget. Therefore, the final optimal remedial plan would be a combination of actions with the highest OAS, which can result in more improvement, and a cost within the annual budget range. If the budget was unlimited and sustainability was not a priority, the combination of remedial actions with the highest OAS would be chosen. In this respect, and in the case of the Werrington Bridge, the combination of major SBGI rehabilitation and BELA replacement resulted in a total OAS of 830.9, met the annual bridge budget request. This information can be transferred directly to the project's asset manager for future remedial planning and management.

5.3. *Visual condition report and remedial plan*

During all these procedures, the designed plugin is utilized to assess all the aforementioned information and update the Werrington BrIM by assigning the analyzed information to each component of the digital model. The system has the ability to colorize the bridge element types with respect to overall maximum interpreted PRCI, shown in Fig. 8, as well as CI values individually, shown in Fig. 6(b). Using this plugin, not only can help with identification of the locality and severity of defects through assignment of geometrical and non-geometrical information of the model, but also can generate a reliable report containing several combinations of remedial actions that can be chosen while keeping the allocated budget optimized.

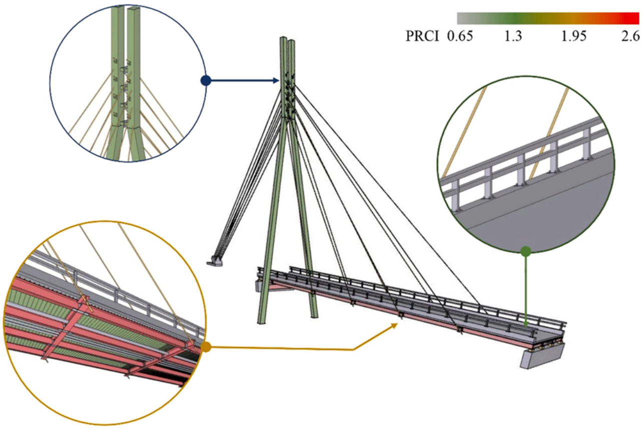


Fig. 8. Visual condition report of Werrington Bridge, PRCI of element types.

6. Discussion and future directions

This research study established a comprehensive methodology and a pathway for addressing two concerns of having a reliable digital replica of the bridge with geometrical and non-geometrical information and employing these data in a reliable and objective management system for remedial planning. In these regards, this study introduced the valuable use of state-of-the-art TLS technology in capturing precise geometrical information of the bridges that can be utilised for 3D CAD model extraction, and digital inspections. Unlike paper-based information, these can be stored in a digital format as a reference for future investigations and are particularly valuable in the development of innovative solutions in detecting damages and identifying risks using clash detection algorithms, which can assist bridge engineers or managers in gaining a better understanding of how the bridge interacts.

The study also made an effort to systematize the bridge management in a practical way, further providing a management system that can be linked to the proposed BrIM and offers asset managers with the ability to use the assigned data to more effectively and objectively evaluate the bridge's health condition. In this system, three supplementary factors were taken into consideration to form a Priority Ranking Condition Index (PRCI), which was used to select those bridge element types that may require more attention in terms of their structural importance, material vulnerability, or other causal factors such as their age or interaction environment.

Besides, a Decision Support System (DSS) was developed to accompany this management system conducting the risk assessment and verifying that the bridge rehabilitation is properly managed. In this regard, a SMART-AHP analysis tool was introduced that integrates asset management system with dynamic risk analysis and strategy mapping for bridge elements, in order to provide a more accurate and objective measure of bridge maintenance plan.

In a subsequent step, the proposed methodology of this research study was then implemented into a software plugin to make this procedure more applicable in terms of Information and Communications Technology (ICT) and digitalization. Eventually, this methodology was further evaluated and validated in a real bridge case study on a cable-stayed bridge named Werrington Bridge in New South Wales, Australia. In this case study, the process from bridge survey through TLS application was covered, and then the general procedure of BrIM development, as well as setting up an asset management plan using DSS was described.

Considering the proposed methodology and findings of this research study, future research could potentially target the incorporation of sustainability into the strategic remedial planning, as well as integration of different methods of real-time data extraction and analysis leveraging Artificial Intelligence (AI) (Liu et al., 2021; Truong-Hong and Lindenbergh, 2022; Yu et al., 2022; Zhen et al., 2022; Yu et al., 2021) to form dynamic bridge digital twins, as well as digital platforms to enable network level asset management and boost capabilities for smart cities and intelligent urban transformation. Implementation of Internet of Things (IoT) in bridge asset management system (Scianna et al., 2022; Wu et al., 2022; El Kadiri et al., 2016), through using remote sensors as a supplement is a suggested solution that not only improves real-time data collection, but also allows for centralizing and correlating data for efficient sharing with network partners and other stakeholders.

7. Conclusion

This paper proposes a novel BrIM-oriented BMS framework with DSS integration which not only incorporates the significance of TLS application for precise bridge inspection, 3D model extraction, as well as supporting the BrIM development in digital transformation of bridge information, but also provides a comprehensive methodology for using BrIM information in a redeveloped element-based condition assessment system while implementing a DSS in decision making that can assist with maintenance planning. This methodology was then employed to develop a software plugin, which was evaluated on a real bridge case study in Australia. The main findings are as follows:

(1) TLS application demonstrates its potential as a ground-based remote system capable of acquiring precise and sufficient data in a timely manner for geometrical bridge inspections. TLS data allows precise surface interpretation, which improves the surface condition assessment, as well as 3D CAD model extraction.

(2) Through the proposed BMS framework, the bridge management system has been greatly improved not only by the BrIM-oriented geometrical and non-geometrical information, but also by the proposed priority ranking and decision support systems. This system surpasses traditional inventory management concepts by providing a visual condition report and proposing a budget-based remedial strategy.

(3) The BMS plugin described in this study provides a new generation of digital documentation system/platform with the flexibility, visuality, and capability to support bridge information for each element that can be readily transferred/shared and be utilized for long-term bridge condition assessments.

(4) The redeveloped condition index concept and proposed PRCI of this research study generated acceptable results in the priority ranking of the Werrington bridge elements. Using PRCI, element types with higher structural importance and material vulnerability received increasing attention with higher PRCI scores.

(5) The integration of DSS into BMS allows higher level of objectivity in decision-making and asset management. This potential has been validated throughout the case study of Werrington Bridge with aim of cost-effective, safe and functional remedial planning.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Masoud Mohammadi reports administrative support and article publishing charges were provided by Western Sydney University.

Data availability

Data will be made available on request.

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