www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

STATE-OF-THE-ART REVIEW ON THE INTEGRATION OF BIM WITH PAVEMENT MANAGEMENT SYSTEMS

SUBMITTED: August 2023
REVISED: October 2023
PUBLISHED: October 2024
EDITOR: Bimal Kumar
DOI: 10.36680/j.itcon.2024.035

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SUMMARY: *Pavement management systems require comprehensive data, including design and existing conditions. These data may be utilised to forecast conditions and determine the optimal timing for implementing maintenance measures to reduce expenses. On the other hand, Building Information Modelling (BIM) technology can be used for organising, managing, and exploiting data to assist decision-makers and ease the extensive pavement management process. It is anticipated that leveraging the capabilities of BIM in the pavement management system will lead to a more productive and streamlined management system. This paper reviews the use of BIM for pavement management and its integration with existing pavement management systems. The scope of the review includes both academic and non-academic literature. Upon review, BIM plays a role in all six steps of pavement management systems. These steps include defining the road network, collecting condition data, predicting pavement conditions, selecting appropriate treatments, reporting results, and choosing the optimal pavement management tools. Several highway agencies that manage road assets may be able to reach maturity level 2. Level 2 maturity in pavement management systems focuses on improving collaborative working methods that lead to automated procedures. Three areas may be the focus of future study. First and foremost is integrating BIM with current survey tools and developing analysis based on regulations for each asset management plan. The second is integrating the analytical process from assessing pavement conditions to choosing maintenance options by considering uncertainty analysis and social factors. The final part is to continue proposing information sharing and an automated pavement management system practice.*

KEYWORDS: *Pavement Management System, Building Information Modelling, review.*

REFERENCE: *Retno Utami, Carlos Osorio-Sandoval, Nicholas Thom (2024). State-of-the-art review on the integration of BIM with pavement management systems. Journal of Information Technology in Construction (ITcon), Vol. 29, pg. 810-825, DOI: 10.36680/j.itcon.2024.035*

1. INTRODUCTION

A pavement management system is used so that roads remain in good condition during their service life. The pavement management process includes maintenance and repairs targeted to achieve a strategy that fits the needs, namely, the right maintenance at the right time to keep costs low. Therefore, a pavement management system must be able to store all information about the pavement, including as-built, existing, and predicted conditions. Improper maintenance timing can result in additional repair costs and other effects, such as long-lasting traffic closures and lane diversions (Shahin, 2005).

Notably, the United States of America's road received a D grade in the infrastructure report card in 2021 because of insufficient funding. Approximately 43% of the system is in poor or average condition, with a $786 billion backlog of road and bridge capital needs. This results for each state Department of Transportation (DOT), which already has its pavement management system, must have adequate plans and improve the system focusing on engineering and economic analysis to solve this issue (Haas, Hudson and Falls, 2015; ASCE, 2021). On the other hand, the UK's road surface is in better condition, with 95% of it not requiring any extra investigation in the next year or two. This is due to a new method that compares actual road surface performance to predicted models, using data and technology for predictive asset management and improved coordination of roadworks (Department for Transport ; UK Roads Liaison Group, 2016; Highways England, 2021). These two conditions show that the UK has found success using data and technology for road management, leading to better decision-making, as seen from the high presentation of good road conditions.

Considering the extensive pavement management process, it is highly desirable to develop intelligent tools that can assist operators during the analytical and decision-making stages (Bosurgi et al., 2020). Several studies have exploited recent technologies for management systems. One of these technologies used and discussed recently is Building Information Modelling (BIM), which allows the creation of digital models. BIM combined with cutting-edge technology for infrastructure management can improve the network's dependability, sustainability, and safety while lowering maintenance costs and hazards and generating significant profits for all stakeholders (Costin et al., 2018).

BIM facilitates collaborative management of transportation assets and networks using open standards, automating processes, and providing asset information to relevant people at the right time (US Department of Transportation Federal Highway Administration, 2021). Appropriately adopting BIM can lead to better decision-making and effective asset activities (Department for Transport ; UK Roads Liaison Group, 2016). However, to fully adopt BIM for infrastructure, there are challenges such as standard neutral exchange format, promotion of interoperability, requirement for digital data to be computable, and integration of information between components (Azhar and Asce, 2011; Costin et al., 2018).

In pavement management, focusing on maintenance and repair practices, the use of BIM has diversified into three main areas: the process of obtaining condition data of road assets (Cafiso et al., 2018; Antonio Biancardo et al., 2021; D'Amico et al., 2022 a; D'amico et al., 2022 b; D'Amico et al., 2023); analysis of decision-making for maintenance of road assets (D'Amico et al., 2021; Bosurgi, Pellegrino and Sollazzo, 2022; Hagedorn et al., 2023; Oreto et al., 2023) and finally life-cycle analysis of assets (Biancardo et al., 2022; Oreto et al., 2022). Even though BIM has arisen as an alternative to existing Pavement Management Systems (PMS), problems in interoperability and data integration problems are still significant issues. Condition data for PMS systems are usually obtained from a visual or non-destructive survey. It needs further analytical tools to obtain conditions based on pavement/road performance indicators before it can be analysed in BIM-based decision-support tools. Furthermore, most PMS systems are presented on Geographical Information Systems (GIS), which have limitations regarding the complete infrastructure model and its components. GIS is used for large-scale infrastructure assessments, whereas BIM can give richer infrastructure details (Bosurgi, Pellegrino and Sollazzo, 2022). These issues highlight the need to improve BIM implementation for pavement maintenance.

From the issues mentioned earlier, the research questions involve (1) how to use BIM for pavement management and (2) how to integrate BIM with current pavement management systems. To respond to these questions, we conducted a literature review on (1) the use of BIM for pavement management and (2) its integration and interoperability with current PMS methods.

This paper is structured as follows. Section 2 describes pavement management systems. Section 3 explains the steps in the pavement management system process. The methodology of this review is defined in Section 4.

Meanwhile, a discussion of BIM in pavement management systems is presented in section 5. Future works can be found in Section 6, and Section 7 gives the conclusion of this paper.

2. PAVEMENT MANAGEMENT SYSTEM

Pavement management is carried out so that the pavement always provides safety and comfort for road users. The context of pavement management is maintaining pavement condition and ensuring that pavement performance is always satisfactory according to the pavement's service life. Pavement management systems implemented in each country may vary. The principle can be observed in Figure 1, where the X-axis represents time or pavement age, and the Y-axis represents low to high degrees. Meanwhile, the blue straight line represents pavement condition, and the red dotted line indicates maintenance cost. Figure 1 illustrates that as pavement ages, its condition deteriorates, and maintenance costs increase over time. Combining these observations leads to the conclusion that significant maintenance costs are required when the pavement's condition reaches a state of failure. To accommodate an ideal pavement management system, a priority analysis of time and cost is needed to predict the future condition of the pavement (Shahin, 2005). In practice, pavement management systems also adhere to the principle of asset management according to ISO 55000, which is stated as the coordinated activity of an organisation to realise value from assets. The realisation of value involves balancing costs, risks, opportunities, and performance benefits (ISO, 2014). Moreover, as part of Transportation Asset Management, PMS has principles to achieve its goals and effectively manage assets. Those principles are policy-driven, performance-based, risk-based, strategically aligned with agency priorities, transparent, information-driven/evidence-based, and option-oriented (American Association of State Highway and Transportation Officials (AASHTO), 2020).

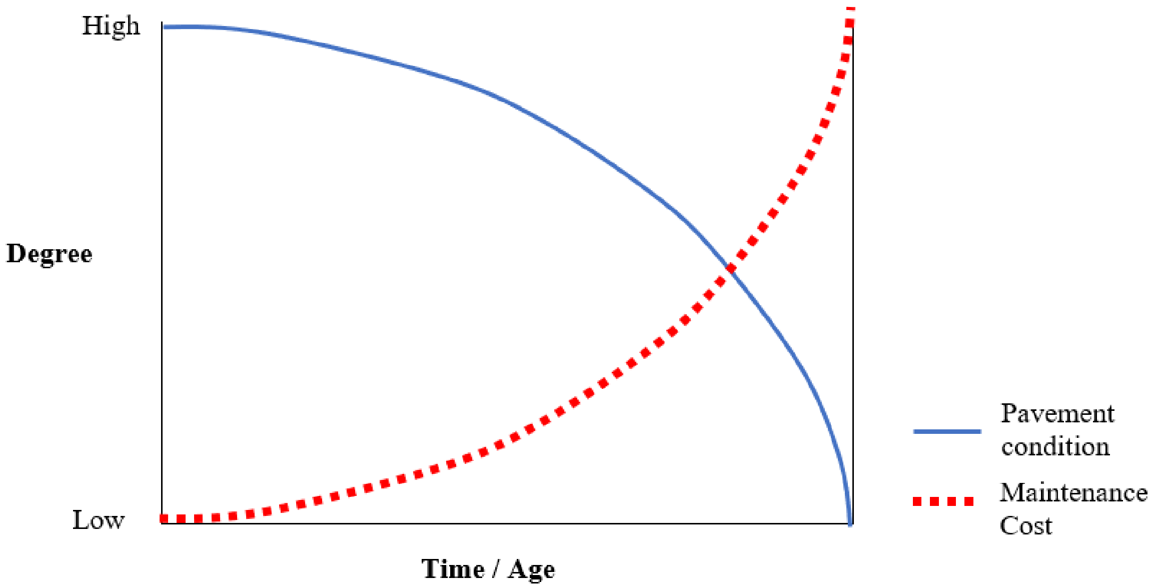

Figure 1: Pavement condition vs maintenance cost throughout pavement age/time.

Adapted from Shahin, 2005.

As an indicator for determining maintenance decisions, pavement management can adopt three approaches, which are reactive-based, interval-based and condition-based. Reactive-based management does not use forecasting to choose the right intervention time. It is important to set minimum acceptable condition standards for highways and create an efficient process for the highway agency in charge of maintenance to complete necessary work within a specified time frame. This will help reduce potential risks and ensure the highest safety standards possible. In interval-based management, intervention is carried out based on the age of the asset; life estimates are used to establish a time interval representative of the service life beyond which the cost of asset failure outweighs the cost of replacement. Interval-based management is commonly applied to operating assets (stripes, signs, guardrails), where just an inventory is maintained. Condition-based management measures the condition of assets and forecasts future conditions so that interventions are carried out based on damage prediction. Thus, condition-based management depends on collecting and analysing asset condition and defect data (American Association of State Highway and Transportation Officials (AASHTO), 2020).

In pavement management analysis, the analysis level hierarchy is divided into two, namely, network level and project level. At the network level, analysis is carried out in several locations that cover a single asset life cycle unit and considers the overall investment that should be allocated to different types of interventions over the network to minimise investment and achieve performance targets or an average condition level (Federal Transit Administration, n.d.). Meanwhile, at the project level, management often includes performing in-depth pavement evaluation and design for the pavement sections in the project. To present the results of the analysis of the pavement management system, the GIS system is used by various agencies (Shahin, 2005; Wolters et al., 2011; American Association of State Highway and Transportation Officials (AASHTO), 2020).

3. STEPS OF A PAVEMENT MANAGEMENT SYSTEM

The agency's goals and objectives are the primary focus of a pavement management system, and asset management is a mechanism for the agency to complete its task more effectively and efficiently while operating within a constrained budget. Agencies may implement various pavement management systems, but the overall process of condition-based pavement management is shown in Table 1.

Table 1: Steps of pavement management system design.

Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
• Define roadway network • Collect inventory information	• Collect condition data • Estimate or measure distress	• Predict pavement condition • Prediction using average deterioration rates or prediction models	• Select treatments • Using cyclical placement or trigger rules • Set treatment priority	• Report result • Using standard or customised result	• Select pavement management tool • Depends on the needs of each agency

Step 7: Keep the process current.

Adapted from Wolters et al., 2011.

The steps of pavement management are described in more detail below (Wolters et al., 2011):

Step 1 is to define the roadway network. In defining a roadway network, dividing roadways into manageable segments is common. These segments are divided based on having similar characteristics, and they are of specific importance since they will serve as the basis for planning future maintenance and rehabilitation projects. Then, inventory data would be collected, such as roadway name, pavement location, pavement dimensions, pavement type, construction history, functional classifications, layer thicknesses, subgrade information, drainage characteristics, ownership information, shoulder data and traffic information.

Step 2 is to collect condition data because condition-based management mainly relies on data-driven decision-making. The condition data can be used to evaluate the overall impact on the network, predict future conditions and define the current status of maintenance and rehabilitation. Meanwhile, condition data is not required for other types of management, such as reactive-based and interval-based management. The data collected for condition-based management should consider the quality and quantity required; more detailed data will require higher cost and time. The data collection process for a PMS, particularly pavement distress data, could be collected manually or automatically using available technologies in each agency.

Step 3 involves predicting the condition of the pavement network using either average deterioration rates or prediction models based on statistical modelling, such as regression analysis. A performance curve produced by analysing historical data, typically in terms of pavement age and quality, could also be employed for predicting future condition. Various agencies may use pavement management software or spreadsheets to develop prediction models. Some agencies are developing more accurate predictive models based on pavement performance and each pavement distress type.

Step 4 is to select treatments for the network. The selection of treatments is based on the triggered condition and analysis of benefit/cost to get ranking priority. Agencies can use two methods of selecting recommended treatment:

cyclical selection or creating treatment rules. Cyclical selection is when maintenance strategies are based on pavement age and repeated at specific intervals. Cyclical treatment selection is ineffective because it creates a uniform treatment for each time interval and is not easily modified to address the placement of the right treatment for each pavement segment independently. Meanwhile, creating treatment rules means that a matrix or decision tree is developed to address the specific condition levels of pavements with specific inventories. Cyclical treatments may be helpful for agencies that use spreadsheets to manage pavement networks, while treatment rules are used by agencies that utilise pavement management software. Then, the agency can use a ranking system or benefit/cost analysis to select a maintenance priority. The ranking process is based on agency priorities, such as pavement condition, functional classification, and traffic level. This process is the simplest method of selecting projects and results in a yearly evaluation of assigned projects. Analysis of benefit/cost gives results for a multi-year period. In terms of recommendations, this analysis considers multiple treatments, the consequences of delaying or accelerating, and each treatment's cost-effectiveness.

Step 5 is to report and share the analysis results with all stakeholders through standard or customised reports. In practice, agencies use several methods of presenting reports, such as maps, tables, or charts.

Step 6 is to select a pavement management tool to store all information and perform analysis, such as a spreadsheet, GIS tool, and pavement management system (public or private). The choice of management tools for each agency may vary depending on its purpose, and it has to balance the cost of the tools. Finally, step 7 ensures the continuity of the pavement management system, making sure that the process follows procedures established in the steps 1 through 6.

4. METHODOLOGY OF REVIEW

Two approaches have been taken in the literature review: published academic articles and non-academic ones such as reports, specifications, and books. Published academic articles were obtained by using established databases such as Scopus and Web of Science. Meanwhile, non-academic sources were identified and obtained from reference lists of journals and articles indexed in Scopus and Web of Science. These non-academic sources, which include standards, specifications, codes, and manuals published by governments and authorities, are crucial for investigating pavement management system.

The keywords used to refine queries in academic databases were “BIM” AND "pavement management system". This search query resulted in 63 results in Scopus and 34 in Web of Science for the period 2013 – 2023. The Scopus search results consist of several types of documents, such as journals, conference paper, conference reviews, book chapters and reviews. Conference reviews were excluded because they were not directly related to the specific titles but rather to the name of the conferences. Therefore, 51 academic references from Scopus were used for further screening in this review. For the Web of Science results, all references were included because the results were limited to articles relevant to the topic. Table 2 lists the search results from those two databases.

Table 2: Findings from a literature search.

Document Type	Scopus	WoS
Article/Journal	28	27
Conference paper/proceeding	17	7
Conference review	12	-
Book chapter	4	-
Review	2	-

Then, a duplicate review process was carried out from both results because many similar articles were found. From this process, 56 references were obtained, including article/journals, conference papers/proceeding, book chapters and review. As seen in Figure 2, the majority of these 56 references originated from Italy and China, with most being produced between 2021 – 2023. This indicates that BIM for pavement management system is a growing area of interest, driven by recent technological advances and implementation of BIM in infrastructure projects.

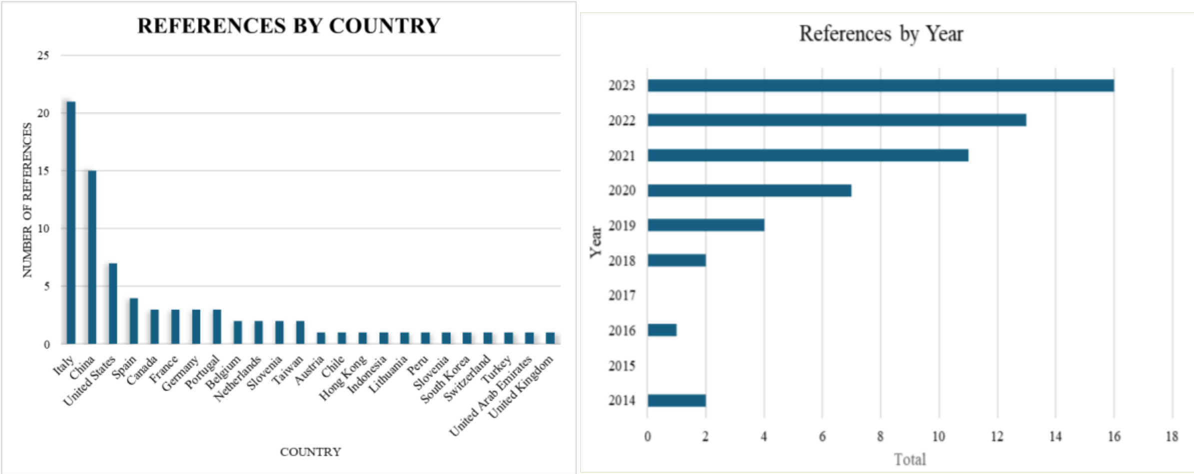

Figure 2: Countries and years of publication.

From those 56 results, a screening of references was achieved by doing backwards snowballing by looking at the title, abstract, and reference list. By this means, 193 references on "bim", "road management", "asset management", "infrastructure management", "pavement management", and extra keywords "integration" and "interoperability" were obtained. The last two keywords were added due to the problems existing pavement management systems have on integration and interoperability.

Then, following the requirements of a literature study, those 193 references were examined. The title and abstract were screened by using the keywords "bim", "pavement", "asset", and "management" as a filter. The accessible journal publications were chosen for the second filter stage, excluding conference proceedings, and open access is preferred. Twenty-seven references were retrieved from this filter step and subsequently examined regarding PMS steps.

5. BIM ON PAVEMENT MANAGEMENT SYSTEM

A road network must be maintained thoroughly always to satisfy users regarding safety, reliability, and reasonable travel times. As stated in the road investment strategy 2020 (UK Department for Transport., 2020), a focus should be placed on effective maintenance using approved management practices, such as lean practice, to maintain road network reliability. Lean practice streamlines project management tasks and enhances productivity through documentation and visualisation tools. According to Koskela and Howell (2002), adopting lean construction is the most efficient approach to designing production systems that reduce waste of material, time, and effort and increase value generation (Abdullah et al., 2009). Effective management is also needed to make the right decisions during the life cycle of built environment assets. Therefore, there needs to be information models and project information models. Information is required during the operations, maintenance, and repair stages, especially for the suggested maintenance plan, such as planned preventative maintenance (British Standards Institution, 2018). In Road Program 2 (July 2020), Highways England (now 'National Highways') will continue to improve road conditions and:

- Be proactive in resolving maintenance issues.
- Manage work programs and operational processes using lean methodologies to increase delivery efficiency.
- Consider how maintenance decision impact road infrastructure's life-cycle cost.
- Reduce maintenance expenses by utilising modern technology.

Furthermore, in UK National Highways' 2025 construction strategy, BIM is intended to reduce costs for construction products and materials. Collaboration across the supply chain will create and use intelligent three-dimensional models and the data and information that goes with them to increase productivity, improve communication, and enable better asset management throughout their lifecycle (Department for Transport ; UK Roads Liaison Group, 2016). Table 3 shows the advantages and potential for adopting BIM for information management on roads, bicycle lanes, and footpaths. The rows of 'advantage' explains areas to improve within the operation and management phase on roads, bicycle lanes, and footpath. While the 'potential' shows the potential result when BIM is applied in the following process.

Table 3: Advantages and potentials of using BIM.

Advantage	Potential
Improve operational processes	Improve accountability for information collection and accuracy.
Improve assurance	Improve collection on financial outruns.
Improve information sharing and collaboration.	Improve access to information.
Improve supply chain management.	Improve different types of information from the supply chain for different assets.
Improve asset data quality.	Confidence in information quality and validity

(Department for Transport ; UK Roads Liaison Group, 2016).

The idea of using BIM for infrastructure is anticipated to be comprehensive throughout the entire life cycle. Agencies must reach BIM maturity level 3 to receive the advantages listed in Table 3, which also calls for a thorough system integration process and a high level of automation. Given the current environment, where there are still a lot of BIM implementations at levels 0 and 1, the most reasonable goal to reach is level 2 (US Department of Transportation Federal Highway Administration, 2021). Level 2 maturity focuses on extracting and integrating data from model files. In level 2 maturity, a focus will be on controlled/automated collaborative working methods (Department for Transport ; UK Roads Liaison Group, 2016). Table 4 indicates that the BIM applications referenced in each review were utilised at specific stages of the pavement management system.

Table 4: References about BIM in the pavement management system.

References	Pavement Management System Steps					
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
(Abbondati et al., 2020)	√					
(Basir et al., 2018)						√
(Antonio Biancardo et al., 2021)	√	√		√		
(Bosurgi, Pellegrino and Sollazzo, 2022)	√	√				√
(Bosurgi et al., 2020)						√
(Boyes, Ellul and Irwin, 2017)						√
(Oreto et al., 2022)	√		√	√	√	√
(Cafiso et al., 2018)	√	√ (no condition indicator)				
(D'Amico et al., 2022)	√	√ (no condition indicator)				
(D'amico et al., 2022)	√	√ (no condition indicator)				
(D'Amico et al., 2021)	√					√
(Hagedorn et al., 2023)						√
(Heikkilä and Marttinen, 2013)	√			√		

(Kazado, Kavgic and Eskicioglu, 2019)	√	√ (no condition indicator)				
(Liu et al., 2021)	√					
(Lu et al., 2011)						√
(Oreto et al., 2023)			√	√	√	√
(Cristina Oreto et al., 2021)	√	√	√	√		
(Liu and Gao, 2017)						√
(Vignali et al., 2021)	√					
(D'Amico et al., 2023)	√	√ (no condition indicator)				
(C. Oreto et al., 2021)	√					

BIM for pavement management is utilised in every step of the pavement management system. Those steps involved defining the road network, collecting condition data, predicting pavement conditions, selecting appropriate treatments, reporting results, and choosing the optimal pavement management tools. As seen in Table 4, most references focus on digitalising road asset data and utilising BIM to deliver effective pavement management. It also indicates that the BIM applications referenced in each review were used at specific steps of the pavement management system. Even though BIM has been applied in various steps of pavement management, there is still room for improvement in utilising it for a comprehensive pavement management process from start to finish. It is also seen in Figure 3 that the utilisation of BIM for digitising and creating an inventory of road assets is the most frequently discussed topic, with 15 references out of the 27 found. Additionally, 10 references highlight that BIM is the chosen technology for storing all information and conducting analyses throughout the entire process of pavement management.

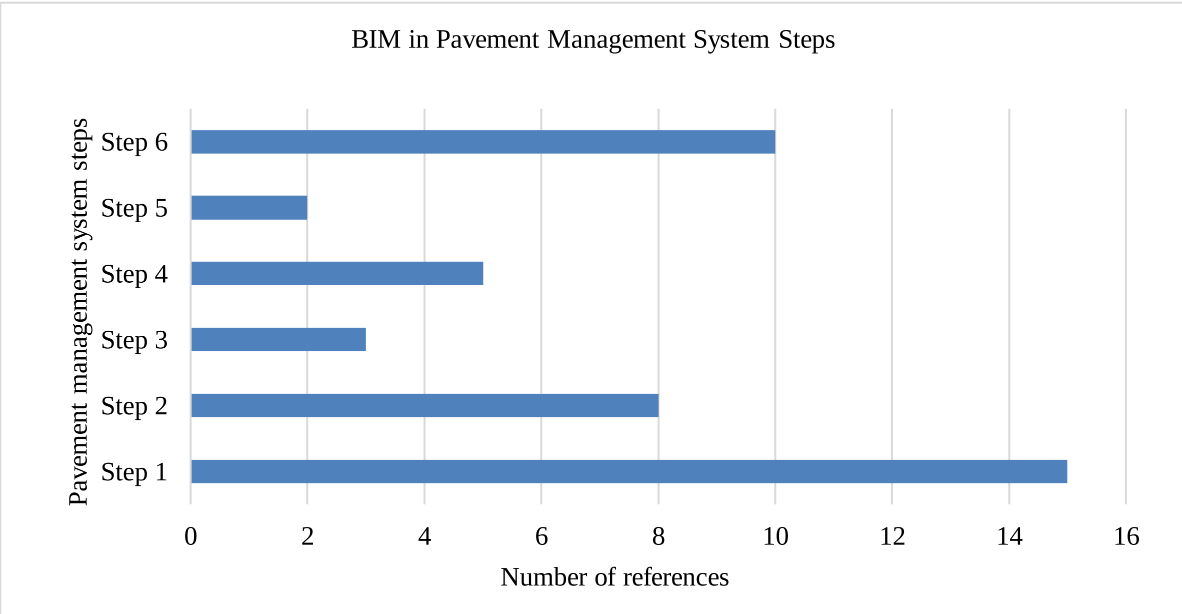

Figure 3: Pavement management system steps discussed in references.

5.1 Step 1: Define the road network

During this stage, BIM is used to create a 3D digital version of the road from the chosen road network to work on. There are two approaches to this stage: creating a road alignment from an available cartographic map (Abbondati et al., 2020; Vignali et al., 2021) or from topographic information gathered through field surveys (Heikkilä and Marttinen, 2013; Cafiso et al., 2018; D'Amico et al., 2022 a; D'amico et al., 2022 b; D'Amico et al., 2023). In the first approach, a Digital Terrain Model (DTM) is obtained from available cartographic maps then a surface model or TIN model is created. Then the horizontal, vertical alignment and a cross-sectional template are modelled. Meanwhile, point cloud data from the second approach's field surveys will be converted into a DTM and used to create alignment, cross-sections, and road surface parametric modelling. This approach will result in more thorough information about the material used and the location and identification of distress. Additionally, models that have been created can be used for a variety of analyses relating to road distress, and they can integrate with information systems about road conditions (D'Amico et al., 2023).

5.2 Step 2: Collect condition data

The 3D digital version of the road network also contains information about road condition data. The road condition data is acquired by several survey techniques, such as the Ground Penetrating Radar (GPR) and Laser Crack Measurement System (LCMS) (Cafiso et al., 2018; D'Amico et al., 2022 a; D'amico et al., 2022 b; D'Amico et al., 2023). The 3D texture of the pavement surface, generated by LCMS, contains enough information for detecting, measuring, and classifying 17 distress types according to Pavement Condition Index (PCI) classification. Meanwhile, other distress types and rating condition calculations (PCI) are identified manually. Then, data treatment and processing were modelled in a collaborative BIM-based delivery approach. The BIM model can contain a high-quality dataset of information obtained through existing survey techniques. As a result, the usage of BIM provides benefits across the asset life cycle (Cafiso et al., 2018).

In another study, BIM is used as a more efficient system to store data and analyse several crucial valuable information for the planning of monitoring procedures and maintenance interventions more effectively. D'Amico et al. (2022 b) implemented a BIM-based integration model between GPR, Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS), and satellite data (from InSAR). In this study, there are three steps of integration. The first is to create a BIM model from GPR and MLS data. This data creates parametric objects such as the road's cross-section. Point cloud from MLS data is extracted into a 3D polyline and obtained as a 3D model of actual object representation. This creates a Digital Terrain Model (DTM) of a real object. Meanwhile, GPR data is extracted to acquire HMA (Hot Mix Asphalt) layer depth. The data contains depth layer values which then can be created as a digital surface. Then, by available software, the data is treated as if it was a point cloud and can be created as a 3D digital model. 3d model from GPR data then being extruded along the infrastructure axis and refers to DTM coordinates as in the 3d model from MLS data. The second step is to create a grid containing satellite data. Satellite data-based InSAR analysis contains remote sensing information that can be incorporated into the digital BIM model. Digital objects transformed from cloud points containing geographical coordinates were geo-referenced. This also contains information on monitoring of road assets. Then, by using Dynamo, that information can be managed and updated. The last step combines the grid containing information data and the BIM model in Revit and creates a digital model containing updated satellite data and monitoring information. Considering BIM emphasises organising, managing, and utilising data to aid decision-making, Revit is one of the tools used to help with the process. Dynamo is visual programming that empowers designers to develop tailored computational design and automation procedures through a visually based node programming interface within Revit. On the other hand, Revit has limitations in exploiting spatial information for infrastructure projects. To address this, Civil3D is used for infrastructure projects, especially road projects.

Meanwhile, other means of analysing road surface conditions are calculating the value of the Present Serviceability Index (PSI), Pavement Condition Index (PCI), Rut Depth and Cumulative Damage. The Present Serviceability Index (PSI) is a synthetic indicator that may be evaluated analytically following an on-site or visually-based assessment of road distress. Pavement sections were made into several sample units for identifying distress (slope variance along the wheel paths, cracking + patching, and rut depth). The Chinese Ministry of Transportation's streamlined method performs automated calculations in determining each pavement segment's Present Condition Index (PCI). Other than - road surface condition indicators, structural indicators such as fatigue damage and rut depth were also analysed. The Verstraeten law predicts rut depth (RD), which should be at most 2 cm for good riding quality. Those analyses use simplified equations to make automation calculation easier by utilising visual script programming in Civil3D named Dynamo (Cristina Oreto et al., 2021).

From Bosurgi (2022), data acquisition, elaboration, and presentation have been performed using Autodesk Civil 3D and Infraworks software. First, specific representation of road axis and transversal sections modelling performed based on Infraworks. A specific coordinate system is selected to represent information and topography coordination. Motorways were modelled by two different planning roads (one for each direction), representing road segments, storing, and displaying all required condition and maintenance information. Target containers were created by a novel feature class for the category 'Roads' in the 'surface layers' of the model and named 'Roads_Conditions'. This becomes a 'target container'. All the fields are empty and will be automatically filled by the second procedure. In the second procedure, through Civil3D stations, Falling Weight Deflectometer (FWD) data were located on the same reference coordinate system by automatically defining coordinate geometry points (COGO points) using latitude and longitude coordinates. To make the import process in the Infraworks feasible, those points were transformed into blocks with specific attributes, representing 'code', and exported in 'SDF' format. Then these points are imported into Infraworks, overlapping with the road models. Other survey datasets were imported to the models, a creation of 'CSV' file containing all the required information of the available survey dataset, a JavaScript routine for reading the external dataset, finding the matching road segment and, thus, filling up all the user-defined attributes have been defined by the authors. To evaluate the segment CSI and update the relative attribute field in the model, a specific pseudocode is used. The last procedure is to define a detailed colouring theme for each reference variable (IRI, RD, SNeff, PCI, etc). Then, CSI was also linked and colour categorised to understand the critical needs of the various segment models.

5.3 Step 3: Predict the condition

BIM-based analytical tools use practical visual programming tools like Dynamo to predict conditions. Several pavement conditions are used as the basis for the input data. Two different prediction scenarios may be employed in the analysis. Pavement condition predictions are possible during both the design and operation-maintenance phases. Prediction models for conditions from the design phase are based on cumulative damage computed from stress and strain integrated with laboratory results (mix design, material characterisation, pavement design phase). Next, determine the cumulative damage limitation and the amount of cumulative damage for the subsequent maintenance task. A life cycle cost analysis (LCCA) is performed after the prediction analysis from the design phase. The calculation of the LCCA indicator of the alternative maintenance strategies of the asphalt layer of a flexible road pavement was implemented as a visual script within Dynamo software aiming to dynamically interact and exchange information in relation to, among others, the chosen design solution with regard to layers thicknesses and main features of the asphalt materials, and the volumes of materials needed for the specific road works (Oreto et al., 2022). The aforementioned prediction model can also analyse construction costs, maintenance expenses, demolition-disposal-recycling costs, and salvage values. A Civil3D extension, Dynamo, that creates a dynamic link between the BIM environment and an open-source visual programming environment was leveraged to equip the pavement BIM with additional analytic tools that run calculations and update the values of the object properties with the outputs of the analyses (Oreto et al., 2023).

Based on the data collected from pavement indicators such as PCI, PSI, rut depth, and cumulative damage, a maintenance analysis can be carried out to predict future conditions. This analysis is performed in a Dynamo environment by defining algorithms to search for the time series of each indicator evaluated in past analyses to reconstruct the future condition of the indicators themselves. A degradation curve is produced from the performance indicators and expressed analytically by interpolating the time series. It shows the change of a status indicator as a function of time and returns the future date at which maintenance intervention will be required. Then, a visual script in Dynamo produces a colour-coded display of pavement conditions. The road highlighted in red indicates the necessity of intervention, yellow highlights severe fatigue cracking, but the overall condition is still above the threshold, and green highlights good pavement conditions (Cristina Oreto et al., 2021).

5.4 Step 4: Select treatment

Pavement condition triggers must be identified before choosing the best maintenance strategy. According to various research, the material and the pavement surface layer's performance can be used to determine the treatment scheme. A ranking algorithm can be used to evaluate treatment by taking % bitumen, stability, and % air voids into account. Each parameter has a score calculated to select the appropriate maintenance following regulations (Antonio Biancardo et al., 2021). According to Oreto et al. (2022), the overall maintenance strategy can be separated into three strategies based on the accumulated fatigue damage analysis. Strategy A entails periodic reconstruction of the wearing course to keep the fatigue damage under the value of 0.2. When the fatigue damage reaches a value of 0,5, Strategy B entails reconstructing the wearing and binder layers regularly. When the fatigue damage comes to a value of 0.9, Strategy C entails reconstructing the entire asphalt pavement (wearing, binder, and base layers) (Oreto et al., 2022).

Determining the priority of maintenance work in the BIM environment can be done by considering the parameters of the minimum service life required for the work, the usable budget, the availability or otherwise of alternative secondary raw materials and cold in-place recycling technology (Cristina Oreto et al., 2021). The sustainability aspect can also be considered in a BIM-LCCA maintenance scheme. In Oreto et al.'s (2022) study, two methods are proposed for BIM-LCCA maintenance design. The first method presents three traditional design options using HMA, with an initial configuration expected to last 18 years. The second method addresses unsatisfactory designs that exhibit surface cracks as early as the eighth year of service life, caused by structural issues like decreased thickness or poor stiffness in asphalt materials and external factors like heavy traffic and atmospheric conditions. The proposed solutions aim to extend the fatigue life of the pavement and reduce the need for maintenance interventions.

To effectively prioritise maintenance, it's essential to integrate pavement management systems (PMS), life cycle cost analysis (LCCA), and multiple attribute decision-making (MADM). PMS provides essential data, while LCCA computes life cycle indicators. Finally, MADM applies budget constraints to arrive at informed decisions (Oreto et al., 2023).

5.5 Step 5: Report result

The results of pavement management analysis are frequently reported in the form of maps shown on a GIS platform. As a result, numerous studies have combined a GIS-based pavement management system with a BIM-based management system. According to the study, integration may be divided into three levels: application, process, and data level. Integration at the data level is the most straightforward level to complete; an illustration for urban development is as follows (Basir et al., 2018):

1. Integrate semantic information from BIM or Industry Foundation Class (IFC) based into City-Geographic Markup Language (CityGML, GIS-based)
2. Combine BIM and GIS in one model, namely the Unified Building Model
3. Develop a new 3D semantic model dedicated to urban development.

In addition to the three approaches mentioned above, a cloud platform for collecting and processing road pavement with multiple sensor data is introduced as a hybrid procedure. The hybrid procedure promotes interoperability, dynamism, sharing, and rapid and error-free handling and analysis of the same data (Bosurgi et al., 2020). However, GIS platforms should not be replaced by BIM-based PMS; instead, they should be integrated into a more comprehensive environment to ensure accurate analyses at all scales. While BIM is more practical for project-level analysis, GIS is better suited for network-level analysis. Direct operations and exploitation of 3D models from smart objects representing their as-built or design status are considered in a BIM-based study (Bosurgi, Pellegrino and Sollazzo, 2022).

Another study (Boyes, Ellul and Irwin, 2017) found that integrating GIS and BIM may be approached from five perspectives: schema, service, ontology, process, and system based. Two critical procedures must be undertaken to accomplish total integration: analysing linking alternatives and validating the selected linking option. The study's limitation is that it requires further discussion on transferring geometry and asset information into GIS, utilising spatial analysis, and looking at integration in semantic-based and ontological-based systems.

An example of linking information between GIS and BIM is promoted using information containers employed by Semantic Web technologies Resource Description Framework (RDF), SPARQL, and R2RML. Cross-domain information containers support an 8-step decision-making process for road maintenance. The first step is to determine the scope of the created information container. Step 2 creates a relational database called the Road Information Database (RIDatabase). This database has four main information components: information about the road sections, information about construction projects related to the road network, information about inspections related to condition information, and information about the maintenance schedule related to forthcoming pavement works. A suitable domain ontology (EUROTL ontology) is used to record the numerical values of the condition and the scheduled maintenance data as step 3. Then, in step 4, the mapping rules for exporting data between relational databases and RDF-based payload triples are defined in the R2RML mapping language. Step 5 is to connect the lane sections from the database to respective IFC elements created and stored in the link set file

Ls_ifc_RIDatabase.rdf. The SPARQL query language may be used to query and filter relevant data to generate the maintenance plan, and queries can be conducted in the platform on aggregated container data as in Step 6. The asset manager creates the maintenance program and includes the relevant data in the information container after examining the query result in Step 7. Step 8, The asset manager can import the appropriate results into the original database (Hagedorn et al., 2023).

Another approach to combining BIM and pavement management systems is the OpenBIM concept. OpenBIM enables users to exchange data transparently and sustainably. The OpenBIM approach also ensures simple data interchange compatibility independent of the platform. However, the IFCroad standard does not address semantic data in the O&M process. Therefore, a single-container attempt was made to expand the IFCroad standard based on the IFCInfra4OM ontology (Ait-Lamallam et al., 2021).

5.6 Step 6: Select a Pavement Management Tool

Meanwhile, for step 6 in the pavement management system steps, it is discussed that highway agencies have options to pick which technologies to deliver its pavement management system. It is also addressed that throughout step 1 – step 5, during the pavement management step, BIM has been elaborated as a tool to deliver effective pavement management. Therefore, further explanation in step 6 is no longer needed.

6. GAPS IN KNOWLEDGE

Two main focuses for knowledge gaps can be identified from the elaboration of the review. The first is enhancing data quality and optimising database management for improving data visualisation, analysis, and reporting capabilities. Big data analysis plays a crucial role in enhancing data quality and efficiency. Exploring applications of big data for prediction model calibration, sensor data integration, and the implementation of technologies such as BIM or OpenData can further enrich this research direction. Existing studies found that there is a discrepancy in data consistency between different platform. Bosurgi (2020), has shown a preliminary evidence of how BIM represent traditional PMS then followed with more comprehensive framework with IBIM methodology (Bosurgi 2022). In contrast, it also shows limitations in enriching and expanding database so that condition management and maintenance planning will be done in a more interoperable, smart and realistic environment (Bosurgi, Pellegrino and Sollazzo, 2022). Research in this area will result in up-to-date and accurate information, increasing the effectiveness of decision-making processes.

The second focus is on integrating emerging technologies such as GIS, BIM, AI, IoT and DLT with PMS. This involves improvement in data collection, analysis and robust decision-making. From the elaboration on BIM integration with PMS, there are still issues in the interoperability at the process level, integration to cover other assets beyond pavements, maintaining data quality during information exchange, scalability and flexibility of data standards, impact of integration on decision-making, data-sharing frameworks and data integration during operations and maintenance phase of pavement. Even though BIM-GIS integration has been initiated in several kinds of research, the limitation persists, especially in geometry transfer, asset information transfer into GIS, spatial analysis, and semantic-based and ontological-based system integration (Boyes, Ellul and Irwin, 2017). Hagedorn (2023) shows the use of the semantic web and information containers could integrate the existing Asset Management System with BIM, yet it still has limitations in full semantic interoperability. Furthermore, the development of IFCRoad (Ait-Lamallam et al., 2021) does not give enough support for semantic data in the operation and maintenance process of road infrastructure. Additionally, a collaborative way of working with the use of ontologies, linked databases and advanced frameworks for pavement management offers novel areas of research to promote the effectiveness of stakeholder collaboration and management process. Research in this area will contribute to effective integration between existing PMS and BIM, improving the efficiency and cost-effectiveness of pavement management practices.

Overall, those two main focuses in knowledge gaps can help bridge current PMS capabilities and emerging practices in improving efficiency, especially in cost-effectiveness and decision-making processes. Future research must be carefully considered, particularly in the context of developing countries with specific requirements and limitations. Those considerations are essential to guarantee that pavement management practices' limitations can be addressed and pavement management purposes can be achieved.

7. DIRECTION OF FUTURE RESEARCH

It has been shown that adequate methods exist for integrating visually-based or tool-aided surveys with BIM. However, the results of this integration need to be applied to different survey methods and survey tools so that each agency can fully adopt the benefits of BIM implementation using various survey tools. It is also necessary to develop analysis tools according to regulations and thresholds for each rule that applies to asset management policies in each agency. In addition, the process of analysing surface conditions has also been carried out with various road condition indicators. However, it is also necessary to add the pavement structure, pavement materials, as well as economic considerations and lifecycle analysis to add to the benefits of the BIM-based management tool that has been developed. Furthermore, it can modify how building sensor technology is implemented to connect field surveys with the BIM modelling (i) Sensor-Revit integration; (ii) Sensor-Revit-Navisworks integration; and (iii) Sensor-Revit-Navisworks-API integration (Kazado, Kavgic and Eskicioglu, 2019).

According to the review elaborated in the previous section, selecting the treatment in BIM-based analysis still requires further research regarding performance-based pavement models. Although integration with the PMS tool for pavement conditions (pavement materials and cumulative damage) has been carried out, the integration from determining pavement conditions to obtaining treatment selection still needs further discussion. In addition, BIM-based treatment selection has yet to discuss uncertainty analysis and social aspects.

Even though successful attempts have been demonstrated in integrating BIM with pavement management systems and GIS, the problem of interoperability and integration between BIM and the latter technologies needs additional study. Moreover, discussion regarding information exchange both semantically and geographically should be addressed more in the maintenance process as well as updating geometric representations.

Another topic of discussion may be a usable information container that permits real-time automatic data. A future discussion should include an automated method to obtain existing asset conditions to enhance automation generation between entities in domain-specific models. According to the digital roadways vision for 2025 (National Highway, 2021), artificial intelligence and machine learning techniques will be utilised to forecast and prevent asset failures. As a result of third-party collaborations and an expanded sensor network, users will have access to more reliable asset and network status data for increased network oversight, enhanced safety, and management. Additionally, further development in the infrastructure of digital twins may be necessary.

8. CONCLUSION

In every step of the PMS process, BIM has been used for pavement management systems. Although obtaining maturity level 3 is still a long process, achieving maturity level 2 may be possible for several agencies that operate road assets. The primary focus on level 2 maturity in Pavement Management Systems is enhancing ways of working that are more collaborative and lead to automation processes.

The first stage of PMS uses BIM to digitally create a three-dimensional version of the road network. Building a road alignment from the available cartographic map and using topographic data acquired from field surveys are the two approaches for digitising. Additionally, collecting condition data can be done by combining on-site surveys using survey vehicles and other visual surveys or relying on a 3D digital representation of the road network. Performance indicators include the Present Serviceability Index (PSI), the Present Condition Index (PCI), the Rut Depth, and the Cumulative Damage. Predicting conditions is the next step in the PMS process, and it is done using visual programming tools like Dynamo. Predictions can be made from the pavement life cycle's design, operation, and maintenance stages. The performance indicators from the previous stage are used as inputs for condition prediction. Furthermore, the treatment plan may be determined by two parameters: the material that comprises the surface layer and the performance of the pavement layer. Visual programming tools like Dynamo are also used in this process. GIS-based and BIM-based methodologies have been integrated into various studies in reporting and choosing an appropriate PMS.

Future research may be conducted in three areas. The first area is integrating existing survey tools and methodologies with BIM and creating regulations-based analyses for each asset management strategy. The second is to combine the analytical process from evaluating pavement conditions to deciding treatment choices considering uncertainty analysis and social aspects so that it leads to a smooth and error-free procedure. The last is to have further discussions about information exchange and an automated technique for pavement management systems.

ACKNOWLEDGEMENT

This work was under a scholarship grant from the Indonesia Endowment Fund for Education (LPDP), Ministry of Finance of the Republic of Indonesia.

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