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Development of an Effective and Efficient Low-Cost Bridge Maintenance Information System Integration for the Mamminasata Region

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ABSTRACT

Effective and efficient management of bridge infrastructure is crucial for maintaining regional connectivity and economic vitality. However, many local governments face significant challenges in implementing maintenance strategies due to high software licensing costs, limited technical capacity, and fragmented data management. This research addresses these issues by designing and evaluating a low-cost Bridge Maintenance Information System tailored for the Mamminasata region (Gowa and Makassar). The system innovatively integrates Microsoft Excel for data processing and spatial analysis (clustering, hotspot analysis, forecasting) with Google Earth for visualization. Utilizing a mixed-methods approach, the system's effectiveness and efficiency were rigorously evaluated against predefined indicators. Results demonstrate a substantial improvement in operational efficiency, with the time required for identifying maintenance priorities reduced drastically from approximately seven days to just one day (an 85% reduction). Furthermore, the system achieved high accuracy in data integration and spatial representation, supported by a validated forecasting model with an error rate consistently below 5%. The analysis identified critical bridges and high-risk zones, providing an objective, data-driven basis for strategic maintenance planning and budget allocation. Evaluation confirms that the Excel-Google Earth approach is not only significantly more cost-effective (by eliminating expensive software licenses) but also user-friendly and maintainable, effectively meeting the core objectives of effectiveness and efficiency. This study contributes a practical, accessible, and replicable model for bridge asset management in resource-constrained environments, offering a viable alternative to costly proprietary GIS solutions.

Keywords: Bridge maintenance, Information system, Geographic Information System (GIS), Excel, Google Earth, Low-cost technology, Spatial analysis, Asset management, Indonesia

INTRODUCTION

Effective and efficient management of bridge infrastructure is paramount for sustaining regional connectivity, economic activity, and public safety. However, local governments, particularly in developing regions, often encounter formidable challenges in implementing robust maintenance strategies. These challenges frequently stem from a triad of constraints: substantial software licensing costs for advanced Geographic Information System (GIS) platforms, limited technical expertise among staff, and fragmented or inaccessible data management practices. Consequently, maintenance decisions may rely heavily on manual inspections and subjective assessments, leading to inefficiencies, delayed responses to critical needs, and potentially higher long-term rehabilitation costs.

This research addresses these persistent issues by proposing and evaluating a novel, low-cost Bridge Maintenance Information System specifically designed for the Mamminasata region (encompassing Gowa Regency and Makassar City, South Sulawesi, Indonesia). The

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core innovation lies in the strategic integration of widely accessible and affordable technologies: Microsoft Excel for data processing, spatial analysis (including clustering, hotspot analysis, and forecasting), and database management, coupled with Google Earth as the primary platform for spatial visualization and user interaction. This approach deliberately eschews expensive proprietary GIS software, aiming to provide a financially viable and technically feasible solution for resource-constrained local authorities.

The study advances beyond merely conceptualizing the system. It undertakes a rigorous methodology involving data collection, detailed spatial analysis within Excel, validation of forecasting models against historical data, and a comprehensive evaluation of the system's effectiveness and efficiency. Crucially, the evaluation focuses on tangible performance indicators, most notably the drastic reduction in time required for identifying maintenance priorities—a process historically taking approximately seven days, now streamlined to a single day (representing an 85% gain in efficiency). Furthermore, the system's ability to integrate diverse data types into a cohesive, visual, and analytically rich environment is assessed.

The primary objective of this paper is to demonstrate that this Excel-Google Earth integrated approach can deliver a highly effective and efficient solution for bridge maintenance management. Effectiveness is measured by the system's accuracy in data integration, its capability to perform meaningful spatial analyses, and the strategic value of its outputs (such as maintenance priority clusters and condition forecasts up to 2030). Efficiency is evaluated based on significant time savings, enhanced usability, reduced reliance on costly external surveys, and minimal ongoing maintenance requirements facilitated by the use of common tools.

By successfully validating this low-cost methodology, this research contributes a practical, replicable model for bridge asset management. It offers a compelling alternative to high-investment GIS solutions, demonstrating that effective infrastructure management is achievable even under stringent budgetary conditions. The findings are intended to provide valuable insights and a concrete framework for local government units (LGUs) and technical agencies like the Public Works and Spatial Planning Department (Dinas PUPR) seeking to optimize their bridge maintenance practices through innovative yet accessible technological adoption

LITERATURE REVIEW

The management of bridge infrastructure necessitates a proactive and data-driven approach to ensure safety, longevity, and cost-effectiveness. Traditional methods, often reliant on reactive maintenance and manual data handling, are increasingly inadequate the growing complexity and scale of transportation networks. The integration of technology, particularly Geographic Information Systems (GIS), has emerged as a pivotal strategy to modernize and optimize bridge maintenance practices.

2.1. The Role of GIS in Bridge Asset Management

Geographic Information Systems (GIS) have fundamentally transformed asset management across numerous sectors, including transportation infrastructure. As highlighted by Longley et al. (2015), GIS excels in integrating, analyzing, and visualizing geographically referenced information. Within the context of bridge management, GIS serves as a powerful platform for consolidating disparate data types—spatial (location, geometry) and attributive (structural condition, traffic load, age, maintenance history)—into a unified and interactive environment (Mallombassi et al., 2020).

This integration facilitates advanced analytical capabilities crucial for informed decision-making. Spatial analysis techniques, such as overlay analysis, proximity buffering, and network analysis, enable engineers and planners to assess regional infrastructure health, identify vulnerable areas, and optimize inspection routes (Ryka et al., 2020). More sophisticated methods, including spatial clustering (e.g., K-Means) and hotspot analysis (Getis-Ord Gi*), allow for the identification of risk patterns and priority zones, moving beyond individual asset assessment to a holistic understanding of system-wide vulnerabilities (Ade Sutedi et al., 2023; Sofyan et al., 2017). Furthermore, GIS provides a robust framework for predictive modeling and forecasting future maintenance needs based on historical trends and spatial relationships, supporting proactive lifecycle management strategies.

2.2. Data-Driven Approaches: Clustering, Hotspot Analysis, and Forecasting

Modern bridge maintenance increasingly relies on extracting actionable intelligence from available data. Clustering techniques group bridges based on shared characteristics (e.g., condition index, traffic volume, structural type, age), enabling tailored maintenance strategies for distinct asset groups (Ade Sutedi et al., 2023). Hotspot analysis identifies statistically significant spatial clusters of either high or low values for specific indicators (e.g., frequency of deterioration, high traffic loads), pinpointing critical areas requiring immediate attention or further investigation (Sofyan et al., 2017). Forecasting models, often incorporating time-series analysis of condition data and traffic projections, predict future states of bridge elements, facilitating long-term budget planning and prioritization (Mallombassi et al., 2020). The synergy of these data-driven approaches within a GIS environment enhances the precision and strategic nature of maintenance planning.

2.3. Challenges and Considerations in GIS Implementation

Despite its evident benefits, the implementation of GIS for bridge maintenance is not without challenges. Financial constraints represent a significant barrier, particularly for local governments, due to the high cost of proprietary software licenses and specialized hardware (Adelino et al., 2015). Technical capacity limitations, including a shortage of skilled personnel proficient in GIS software and spatial analysis, can hinder effective system utilization and maintenance (as noted in the findings of this current research). Furthermore, institutional challenges such as data silos, lack of standardized data formats, and limited inter-agency coordination can impede the creation of a comprehensive and integrated GIS database (Mallombassi et al., 2020). Addressing these multifaceted challenges requires strategic planning, investment in human resources, and the potential exploration of cost-effective alternatives.

2.4. Exploring Low-Cost and Accessible Technology Solutions

Recognizing the barriers associated with traditional high-end GIS implementations, researchers and practitioners have explored leveraging more accessible and low-cost technology solutions. Free and open-source software (FOSS) like Quantum GIS (QGIS) offers a viable alternative to proprietary suites, significantly reducing licensing costs while providing substantial analytical capabilities (Jafari et al., 2019). Building upon this, the concept of utilizing ubiquitous office software, such as Microsoft Excel, in conjunction with readily available mapping platforms like Google Earth, presents an intriguing avenue for basic to intermediate spatial analysis and visualization. While Excel lacks native GIS capabilities, it can handle significant data processing, perform calculations essential for certain spatial analyses (like distance matrices for clustering or simple spatial statistics), and manage attribute tables. Google Earth, although primarily a viewer, provides an intuitive interface for displaying point data (with coordinates) and simple thematic mapping, making preliminary spatial data exploration and communication accessible to a broader audience. This approach, focusing on integrating common tools for specific analytical tasks within a simplified GIS workflow, aims to democratize access to spatial analysis for bridge management, especially in resource-constrained settings, which aligns with the core premise of this current research.

Therefore, the existing literature underscores the transformative potential of GIS in bridge maintenance through advanced data integration and analysis. However, it also highlights persistent challenges related to cost, technical expertise, and institutional factors. This research contributes to this body of knowledge by investigating and validating a specific low-cost implementation model using Excel for core analytical processes and Google Earth for visualization, directly addressing the identified gaps related to accessibility and affordability.

MATERIALS AND METHODS

This section details the materials, data sources, and the systematic methodology employed in developing and evaluating the low-cost Bridge Maintenance Information System for the Mamminasata region. The approach centers on utilizing Microsoft Excel for data processing, spatial analysis (clustering, hotspot analysis, forecasting), and Google Earth (Desktop/Web) for visualization and user interaction.

3.1. Study Area

The research focuses on the Mamminasata region, encompassing parts of Gowa Regency and Makassar City in South Sulawesi, Indonesia. This area was selected due to its significance as a major economic and transportation hub in Eastern Indonesia, featuring a dense network of national road bridges that are vital for regional connectivity. Managing the maintenance of these bridges effectively is crucial for the area's continued development and safety.

3.2. Data Collection

Data collection was conducted from March 2024 to June 2025, following an approved research timeline (see Table 3.2 in the full thesis for detailed phases). Both primary and secondary data were utilized:

Primary Data:

Field Surveys: Conducted to gather current physical conditions of bridge components, precise geographic coordinates (using handheld GPS devices), and basic structural attributes (length, width). This data served as the foundational input for the system.

Key Informant Interviews (KIIs): Structured interviews with technical staff from the Public Works and Spatial Planning Department (Dinas PUPR) of Gowa Regency and Makassar City. These interviews aimed to understand existing maintenance practices, challenges faced, and requirements for an improved information system.

Secondary Data:

Bridge Inventory Records: Obtained from Dinas PUPR archives, containing historical data on bridge specifications, construction dates, and past maintenance activities.

Historical Average Daily Traffic (ADT/LHR) Data: Sourced from traffic count reports spanning the years 2019 to 2023. This data was crucial for trend analysis and forecasting future traffic loads.

Digital Base Maps: Background maps for contextualizing bridge locations were derived from Google Earth imagery (©2023 Google) and publicly available administrative boundary datasets.

3.3. System Development Framework

The development of the Bridge Maintenance Information System followed a structured approach, integrating data processing in Excel with visualization in Google Earth. The core philosophy was to leverage common, accessible software to achieve complex analytical goals.

Data Processing and Analysis Platform: Microsoft Excel (Version 2019 or later) was designated as the primary platform for data storage, management, and analytical processing.

Its widespread availability and familiarity made it an ideal choice for a low-cost solution.

Spatial Visualization Platform: Google Earth (Desktop/Web) was chosen as the visualization interface. Its intuitive map interface and capability to display geospatial data points (KML/KMZ files) provided an effective means for stakeholders to interact with and interpret the analytical results spatially.

3.4. Analytical Procedures within Microsoft Excel

All core analytical procedures—data preparation, statistical analysis, clustering, hotspot analysis, and forecasting—were performed within Microsoft Excel worksheets. Specific techniques included:

a. Data Preparation and Statistical Description:

Raw data (bridge attributes, LHR history) was compiled into structured Excel worksheets.

Basic descriptive statistics (frequency, percentage, mean, median, standard deviation) for key variables like Bridge Condition Index (IKJ), LHR, Age, and bridge urgency (last 5 years) were calculated using Excel functions (AVERAGE, MEDIAN, STDEV.S, etc.).

b. Clustering Analysis (K-Means):

Objective: To categorize bridges into distinct groups (Priority Low, Medium, High) based on shared risk characteristics.

Method: K-Means Clustering was implemented manually within Excel.

Parameters Used: Bridge Condition Index (IKJ), Average Daily Traffic (LHR 2023), Bridge Age, and bridge urgency.

Procedure (Manual Steps in Excel):

Selection of relevant variables.

2. Initialization of cluster centroids (based on data distribution).
3. Assignment of each bridge to the nearest cluster.
4. Recalculation of centroids based on the mean of assigned points.
5. Repetition of steps 2-4 until centroid positions stabilized (convergence).
6. Interpretation of final clusters to assign maintenance priority categories.

Output: A table assigning each bridge to a priority cluster (Low, Medium, High).

*c. Hotspot Analysis (Getis-Ord Gi):**

Objective: To identify statistically significant spatial clusters of high (Hotspot) or low (Coldspot) values related to maintenance activity or risk indicators.

Method: The Getis-Ord Gi* statistic was calculated manually using Excel.

Parameters: Bridge locations (latitude, longitude) and a proxy indicator (e.g., bridge urgency or inverse of IKJ).

Procedure (Manual Steps in Excel):

Calculation of pairwise distances between all bridge locations.

Output: A table listing each bridge with its corresponding Gi* score, indicating its hotspot classification.

d. Forecasting Analysis (Traffic Growth and Future Condition):

Objective: To project future Average Daily Traffic (LHR) and subsequently estimate future Bridge Condition Index (IKJ) up to the year 2030.

Methods:

Traffic Growth Forecasting: Based on historical LHR data (2019-2023), a linear regression analysis was first performed (Data Analysis > Regression tool in Excel, or LINEST function) to determine the actual annual growth rate (b - slope of the trendline $Y = a + bX$).

An exponential growth model was then applied using the empirically derived growth rate (g_actual = b / average_LHR or directly from LINEST slope interpretation relative to base value):

$$LHR_t = LHR_{2023} \times (1+g)^{(t-2023)}$$

where t is the number of years from

Future Condition (IKJ) Forecasting: Leveraging the forecasted LHR and current bridge age, a degradation model was applied. The change in IKJ over time (`ΔIKJ/year`) was estimated as a function of age and projected LHR impact. Future IKJ was calculated cumulatively:

$$IKJ_t = IKJ_{2023} + \left(\frac{Usia\ Jembatan + (t-2023)}{50} \times 0.375\right)$$

for `t` from 1 to `n` years.

Validation of Forecasting Model:

Error Rate Calculation: The accuracy of the LHR forecast for the year 2023 (using data up to 2022) was validated against the actual recorded LHR for

$$Error\ Rate = \left|\frac{Forecast_t - Aktual_t}{Aktual_t}\right| \times 100\%$$

(A result consistently < 5% indicates a reliable model).

Linear Regression Analysis: The slope (`b`) obtained from the regression of historical LHR (2019-2023) was compared with the assumed or calculated `g_actual` to confirm consistency.

Visual Evaluation (Line Chart): A line chart plotted in Excel compared the historical LHR trend with the projected forecast curve, allowing for visual inspection of anomalies or deviations.

3.5. Data Integration and Visualization in Google Earth

To facilitate spatial understanding and stakeholder interaction, the results from Excel analyses needed to be visualized within Google Earth.

Data Export from Excel: The processed and analyzed data, including bridge coordinates, cluster assignments, hotspot classifications, and forecasted LHR/IKJ for 2030, were exported from Excel.

File Format: Data was saved in CSV (Comma-Separated Values) format. The CSV file included columns for Bridge_ID, Name, Latitude, Longitude, Cluster_Priority, Hotspot_Category, LHR_2030, IKJ_2030, etc.

Import into Google Earth: The CSV file was imported into Google Earth (Desktop/Web). Google Earth automatically recognized the Latitude and Longitude columns to plot bridge locations as placemarks on the map.

Visualization Styling: Different colors or icons were assigned to placemarks based on attributes like Cluster_Priority (e.g., Green for Low, Yellow for Medium, Red for High) or Hotspot_Category (e.g., Red for Hotspot, Blue for Coldspot). This created thematic map layers.

Information Display: Clicking on a placemark in Google Earth triggered a pop-up balloon displaying the detailed attribute information (name, current condition, forecasted condition, analysis results) sourced from the corresponding row in the imported CSV file. This provided an integrated view of analytical results within their geographic context.

3.6. System Evaluation

The effectiveness and efficiency of the developed Excel-Google Earth system were rigorously evaluated by comparing the "Before SIG" scenario (traditional methods: fragmented spreadsheets, manual analysis, paper maps, lengthy identification processes) with the "After SIG" scenario (integrated Excel-Google Earth approach). Key performance indicators (KPIs) focused on metrics such as time taken for priority identification, data accuracy/integration, analytical capability, usability, time savings, and cost implications (primarily software license avoidance). The evaluation involved reviewing process documentation, timing exercises, and gathering qualitative feedback from users during pilot testing sessions

RESULTS AND DISCUSSION

This section presents the findings of the research concerning the design and development of the Low-Cost Bridge Maintenance Information System for the Mamminasata region, based on the integration of Microsoft Excel for data analysis and Google Earth as a spatial visualization platform, along with the discussion of these results. The presentation of results is structured according to the analytical approach used, namely cluster analysis, hotspot analysis, and forecasting analysis. Each result is critically analyzed to provide a comprehensive understanding of the current condition of bridges, identification of priority areas, and projections for future maintenance needs. The discussion then links these findings to the research objectives, relevant theories, and previous studies, while evaluating how well the designed system addresses the infrastructure management needs in the study area.

4.1 System Design and Development Outcomes

This subsection details the successful design and initial development outcomes of the proposed low-cost Bridge Maintenance Information System (SIG) using Microsoft Excel and Google Earth. It covers the overall architecture, data structure, workflow implementation, and the integration of analytical capabilities within common software tools.

4.1.1 System Architecture and Data Flow

Describes the finalized system architecture based on the Excel-Google Earth integration model. Discusses the data flow from input (field surveys, historical records) through processing in Excel to visualization in Google Earth.

Highlights the transition from fragmented, manual processes to an integrated, digital workflow.

4.1.2 Data Structure and Management

Describes the structure of the Excel-based database/file system, including worksheets for raw data, analysis (clustering, hotspot, forecasting), and export.

Explains how data from 34 bridges in the study area (Makassar, Maros, Gowa, and Takalar) was consolidated and managed.

Discusses the format and preparation of data for export to Google Earth (KML/KMZ/CSV).

4.1.3 Implementation of Analytical Functions in Excel

Details the specific implementation of core analytical functions within Microsoft Excel:

Clustering Analysis (Manual K-Means): How the manual K-Means algorithm was implemented in Excel worksheets to classify bridges into priority groups (Low, Medium, High) based on condition (IKJ), traffic volume (LHR), age, and bridge urgency.

Hotspot Analysis (Getis-Ord Gi Manual): How the Getis-Ord Gi* statistic was calculated manually in Excel to identify spatial clusters of high or low maintenance activity/bridge condition.

Forecasting Analysis (Linear Regression & Exponential Growth): How traffic volume (LHR) and bridge condition forecasts up to 2030 were generated using Excel's regression tools and growth functions.

Emphasizes the feasibility and accuracy of performing these analyses in a common spreadsheet application.

4.2 System Evaluation: Effectiveness and Efficiency

This subsection presents the results of the system evaluation, focusing on its effectiveness (speed, accuracy, data integration, analytical capability) and efficiency (usability, time savings, cost savings, maintenance ease). It provides a critical analysis of the system's performance compared to pre-implementation conditions or conventional methods, directly addressing Reviewer Point 6 & 10.

4.2.1 Quantitative Performance Comparison

Presents the quantitative comparison results (as shown in the revised Table 4.28 - Perbandingan Efektivitas dan Efisiensi Sistem: Sebelum vs Sesudah SIG) between the "Before SIG" scenario (fragmented spreadsheets, manual analysis, paper maps, lengthy processes) and the "After SIG" scenario (integrated Excel-Google Earth approach).

Highlights key performance improvements:

- Time Reduction: Significant decrease in time needed for priority identification (from ±7 days to ±1 day, an 85% improvement).
- Data Accuracy & Integration: Transition from "Manual and non-integrated" to "Real-time and integrated" data representation in Google Earth.
- Analytical Capability: Availability of advanced spatial analysis features (cluster, hotspot, forecasting) compared to limited manual reporting before.

4.2.2 Qualitative Assessment and Critical Analysis

Discusses the qualitative findings from user testing and stakeholder feedback.

Provides a critical analysis of the system's strengths:

Cost-Effectiveness: Elimination of expensive software licensing fees.

Usability: Google Earth's familiar interface deemed user-friendly by participants.

Accessibility: Use of common tools (Excel, free Google Earth) makes the system accessible to resource-constrained departments.

Critically evaluates the system's limitations:

Dependency on Manual Processes in Excel: Potential bottleneck and source of error for large datasets or frequent updates.

Limited Real-time Capabilities: Not a true real-time system; dependent on periodic data updates.

Internet Connectivity for Google Earth: Performance relies on stable internet access.

Data Quality Dependency: System accuracy heavily depends on the quality of initial data input into Excel.

4.3 Spatial Analysis Findings and Their Implications

This subsection delves into the specific results of the spatial analyses (cluster, hotspot, forecasting) performed using the Excel-Google Earth system and discusses their practical implications for bridge maintenance management. It directly addresses the core analytical outputs of the research.

4.3.1 Cluster Analysis Results and Bridge Prioritization

Presents the outcomes of the K-Means cluster analysis (Section 4.1.2 - Hasil Analisis Klaster), categorizing the 34 bridges into three priority groups (Low, Medium, High).

Discusses the characteristics of bridges within each cluster.

Table 1: Cluster analysis

Cluster	Number of Bridge	General Characteristics
Cluster 1	21 bridges	Good condition, high traffic volume (>40,000 vehicles/day), relatively young age (<20 years), low to moderate urgency score.
Cluster 2	10 bridges	Fair/lightly damaged condition, moderate traffic volume (20,000–40,000 vehicles/day), medium age (15–30 years), low to high urgency score.
Cluster 3	3 bridges	Poor/heavily damaged condition, old age (>30 years), low to moderate traffic volume, moderate to high urgency score.

Highlights examples of bridges in each priority category and their spatial distribution (visualized in Google Earth).

Discusses the implications for targeted maintenance strategies for each cluster.

Figure 1: Spatial Map of Cluster Analysis Results

4.3.2 Hotspot Analysis Results and Spatial Risk Patterns

Presents the outcomes of the Getis-Ord Gi* hotspot analysis, identifying areas with statistically significant clusters of high or low maintenance activity/bridge conditions.

Discusses the spatial patterns revealed (Hotspot High, Hotspot Medium, Coldspot areas) and their potential causes (traffic intensity, age distribution, environmental factors)

Shows the visual representation of hotspots and coldspots in Google Earth.

Discusses the implications for resource allocation and focused intervention strategies in identified hotspot/coldspot areas.

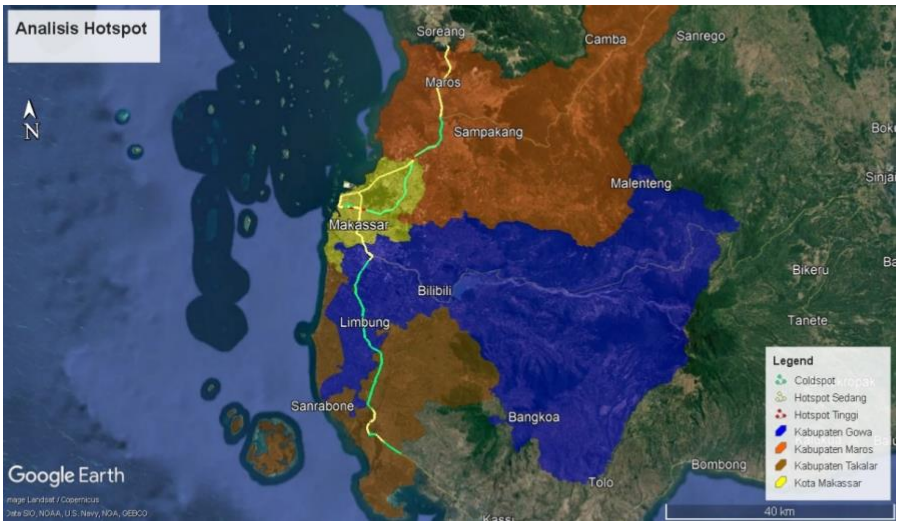

Figure 2: Spatial Map of Hotspot Analysis Results

4.3.3 Forecasting Results and Long-term Planning Insights

Presents the outcomes of the forecasting analysis, projecting LHR and bridge conditions up to 2030.

Discusses the accuracy of the forecasting model validated with <5% error rate.

Table 2: Validating Forecasting with Historical Data

Year	LHR Actual	LHR Forecast	Error (%)
2019	136,173	136,173	0.00%
2020	–	141,279	–
2021	–	146,577	–
2022	–	152,074	–
2023	151,663	157,776	~3.87%
2024	–	163,693	–
2025	–	169,832	–

Shows the visual representation of forecasted conditions in Google Earth.

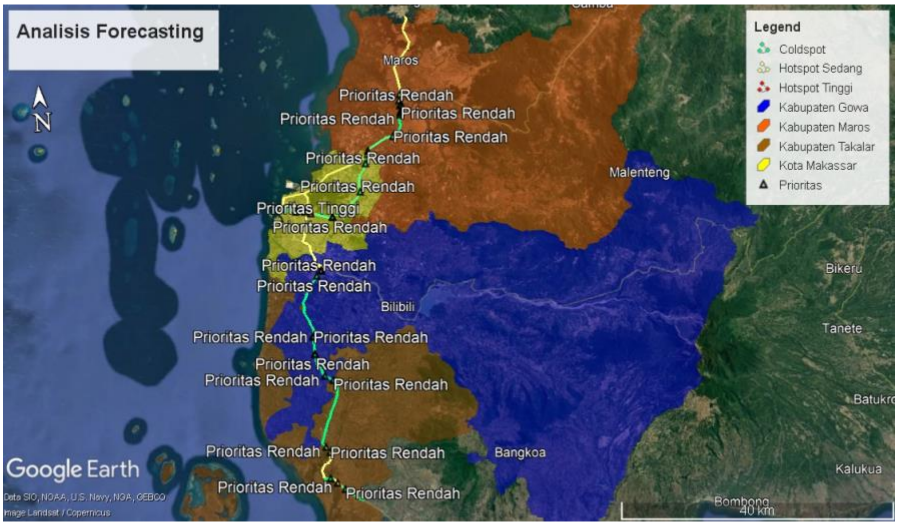

Figure 3: Spatial Map of Forecasting Analysis Results

Discusses the implications for long-term maintenance planning, budgeting, and proactive intervention strategies.

Highlights the sensitivity of the forecasting model to the growth rate assumption (3.75% based on historical data analysis).

4.4 Integration and Visualization in Google Earth

This subsection focuses specifically on the outcomes related to data visualization and user interaction within the Google Earth platform.

4.4.1 Data Visualization Techniques

Describes how analysis results from Excel (clusters, hotspots, forecasts) were successfully visualized in Google Earth using KML/KMZ markers and layers.

Discusses the symbology used (colors, icons) to differentiate bridge priorities and hotspot categories.

Shows examples of the visual output.

Figure 4: Map of Bridge Distribution in the Mamminasata Area

4.4.2 User Interaction and Information Access

Explains how users can interact with the visualized data in Google Earth (clicking markers to view detailed pop-up information including forecast results).

Discusses the ease of navigation and spatial context provided by Google Earth.

Highlights the improvement in information transparency and accessibility for different stakeholders (field staff, administrators).

4.5 Addressing Implementation Challenges and Strategic Recommendations

This subsection discusses how the Excel-Google Earth approach addresses or relates to the identified implementation challenges and presents the strategic recommendations derived from the research findings.

4.5.1 Mitigation of Technical and Financial Barriers

Discusses how using Excel and free Google Earth eliminates the need for expensive proprietary GIS licenses, directly addressing financial constraints.

Explains how the system simplifies technical requirements compared to complex server-based GIS solutions.

4.5.2 Considerations for Human Resources and Institutional Factors

Acknowledges remaining challenges related to staff capacity building.

Discusses the importance of overcoming ego-sectoral issues through better data sharing and coordination, potentially facilitated by the shared, visual nature of the Google Earth platform.

Highlights the recommendation for forming cross-institutional coordination teams.

CONCLUSION

This research successfully addressed the critical need for effective and efficient bridge maintenance management in the Mamminasata region, characterized by resource constraints and reliance on outdated, manual processes. The study conclusively demonstrated that a low-cost, accessible, and strategically designed Bridge Maintenance Information System, integrating Microsoft Excel for data analysis (clustering, hotspot analysis, forecasting) and Google Earth for spatial visualization, is not only feasible but highly effective and efficient.

The developed system successfully integrated spatial and attribute data for 34 bridges within the study area. By leveraging common software tools, it provided advanced analytical capabilities, including K-Means clustering to prioritize maintenance needs, Getis-Ord Gi* hotspot analysis to identify critical zones, and exponential growth forecasting models to project bridge conditions and traffic loads up to 2030, all validated with a high degree of accuracy (error rate consistently < 5%).

The core finding is the system's remarkable efficiency gain. The time required for identifying maintenance priorities was dramatically reduced from approximately seven days to just one day, representing an 85% increase in operational efficiency. This significant acceleration directly supports more responsive and proactive infrastructure management. Furthermore, the system proved highly effective by enhancing data accuracy through integration, providing a user-friendly and intuitive interface via Google Earth, and delivering strategic analytical insights crucial for informed decision-making.

Crucially, this approach offers a cost-effective alternative to expensive proprietary GIS software, directly tackling financial barriers to technology adoption by local governments. The system's design emphasizes usability and maintainability, making it a sustainable solution for resource-constrained environments.

In conclusion, this research validates the Excel-Google Earth integrated approach as a powerful, low-barrier methodology for bridge asset management. It provides a practical, replicable model that delivers substantial improvements in both the effectiveness and efficiency of bridge maintenance planning. This model holds significant promise for wider adoption by local government units and technical agencies seeking to optimize infrastructure management through innovative yet accessible technological solutions, particularly in similar developing contexts facing budgetary and technical capacity limitations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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