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Integrated BIM-GIS Framework for Asset Management of National Road Bridge Inventories

Aduot Madit Anhiem
Research Affiliation: UNICAF / Liverpool John Moores University, Liverpool, UK; UniAthena / Guglielmo Marconi University, Rome, Italy
Email: aduot.madit2022@gmail.com | rigkher@gmail.com

ABSTRACT

anagement of national road bridge inventories in developing regions is constrained by fragmented data systems, limited monitoring capacity, and the absence of integrated decision-support frameworks capable of translating condition data into prioritised maintenance programmes. This paper presents the design, formalisation, and validation of an integrated Building Information Modelling–Geographic Information Systems (BIM-GIS) framework for the lifecycle asset management of national road bridge inventories, with particular application to the South Sudan national road network and the broader East African Community (EAC) infrastructure corridor. The framework establishes a bidirectional data exchange architecture between IFC-compliant BIM models and georeferenced GIS databases, enabling simultaneous geometric, structural, and spatial analysis of bridge assets within a unified platform. A formal data schema is developed that maps structural element attributes — including material properties, condition ratings, inspection histories, and maintenance records — to geospatial objects with full topological relationships to the road network. Mathematical formulations for condition index computation, deterioration prediction using Markov chain transition matrices, and maintenance prioritisation using multi-criteria decision analysis (MCDA) are derived and implemented within the framework. Spatial query performance benchmarks demonstrate that the BIM-GIS integrated system achieves a 62% reduction in query response time for asset inventories exceeding 10,000 bridge records compared to non-indexed GIS systems. Lifecycle cost analysis shows a net present value saving of approximately USD 2.4 million per 100 km of national highway over a 50-year analysis horizon when the BIM-GIS optimised maintenance programme replaces reactive maintenance. The framework is validated against a prototype inventory of 47 bridges on the Juba–Nimule highway corridor, demonstrating practical implementation feasibility within the existing institutional and technical capacity of the Ministry of Roads and Bridges. Recommendations for phased national roll-out and for GIS interoperability with international road asset management standards are presented.

ords: *BIM; GIS; bridge asset management; road infrastructure; IFC; condition index; Markov chain; MCDA; South Sudan; East Africa*

1. Introduction

Road bridge infrastructure is among the most capital-intensive and strategically critical components of national transport networks. The deterioration of bridges — caused by structural ageing, traffic overloading, flooding, deferred maintenance, and material degradation — reduces network connectivity, raises transport costs, and, in extreme cases, causes catastrophic structural failure with severe humanitarian consequences. Effective lifecycle management of bridge assets therefore demands timely, spatially accurate, and analytically rigorous information systems that can support evidence-based intervention decisions at both the network and project levels ((Zavadskas et al., 2007); (Thompson et al., 2012)).

In sub-Saharan Africa, the challenge of bridge asset management is compounded by four structural constraints: ((Omar & Nehdi, 2018)) the majority of bridge inventories are poorly documented, with condition records maintained in heterogeneous paper or spreadsheet formats that cannot be queried at scale; ((Agrawal et al., 2010)) the institutional capacity for systematic bridge inspection and structural assessment is limited, resulting in inspection cycles that may extend to 5 to 10 years rather than the 2-year cycles recommended by AASHTO and FHWA; ((Aien et al., 2014)) road authorities face severe budget constraints that necessitate rigorous prioritisation of maintenance interventions to maximise the value of scarce expenditure; and ((Ni et al., 2012)) the spatial distribution of assets across large, poorly accessible territories with limited telecommunications connectivity makes centralised data collection and analysis logistically challenging ((Wilkinson et al., 2022); MoRB, 2023).

Building Information Modelling (BIM) and Geographic Information Systems (GIS) represent two powerful but historically siloed technologies that, when integrated, address complementary aspects of these challenges. BIM provides a rich, parametric, object-oriented representation of individual structures — capturing geometry, material properties, structural analysis results, and inspection data at element level — while GIS provides the spatial context, network connectivity, and population-level analytics necessary for system-wide asset management decisions ((Nagel et al., 2009); (Olawumi et al., 2017)). Despite this complementarity, the BIM-GIS integration literature has focused predominantly on building and urban infrastructure in high-income settings, and the specific requirements of national road bridge inventory management in developing country contexts have received limited attention.

This paper addresses this gap through the following principal contributions: ((Omar & Nehdi, 2018)) development of a formal BIM-GIS data schema for bridge asset management with IFC-GIS bidirectional mapping; ((Agrawal et al., 2010)) mathematical formulation of condition index computation, Markov chain deterioration modelling, and MCDA-based maintenance prioritisation; ((Aien et al., 2014)) spatial query performance benchmarking for large bridge inventories; ((Ni et al., 2012)) lifecycle cost analysis demonstrating the economic case for BIM-GIS adoption; and ((Argüelles-Fraga et al., 2013)) validation of the framework on a prototype 47-bridge inventory of the Juba–Nimule highway, South Sudan.

2. Theoretical Framework

2.1 BIM-GIS Integration Architecture

The integration of BIM and GIS data models requires resolution of four fundamental technical challenges: geometric representation, coordinate reference systems, semantic data models, and update synchronisation. The proposed framework addresses each through a four-layer architecture:

Layer 1 (Geometry): BIM models (IFC format) use a local Cartesian coordinate system referenced to a project origin, while GIS data is referenced to a geodetic coordinate reference system (CRS). The transformation between BIM local coordinates (x_b, y_b, z_b) and GIS geographic coordinates (lambda, phi, h) is achieved through a georeferencing transformation matrix T:

((Omar & Nehdi, 2018))

$$\begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix} = [T] \begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}$$

where T is a 3×3 rotation–scaling matrix and [t_x, t_y, t_z]^T is the translation vector from BIM origin to the GIS projected coordinate origin. For the South Sudan national coordinate system (Sudan National Grid, based on the Adindan datum), the required affine parameters were determined through a minimum of four control points measured by differential GPS.

Layer 2 (Semantics): IFC object classes (IfcBridge, IfcBeam, IfcSlab, IfcFoundation) are mapped to GIS feature classes through a formal ontology expressed in OWL (Web Ontology Language), enabling bidirectional attribute translation and maintaining referential integrity between the structural model and the spatial inventory.

Layer 3 (Topology): Bridge features are topologically related to the road network GIS layer using a node-edge graph representation, enabling network-level queries such as bridge-dependent connectivity analysis and route vulnerability assessment.

Layer 4 (Synchronisation): A change-detection algorithm compares attribute hash values between BIM and GIS records at each synchronisation event (triggered by inspection, maintenance, or structural modification), propagating only changed records to reduce data transfer overhead.

2.2 Condition Index Formulation

The Bridge Condition Index (BCI) for asset i is computed as a weighted sum of element-level condition scores:

((Agrawal et al., 2010))

$$BCI_i = \frac{\sum_{j=1}^{n_e}(w_j \cdot C_j \cdot A_j)}{\sum_{j=1}^{n_e}(w_j \cdot A_j)}$$

where Cj is the condition rating of element j on a scale of 0 (failed) to 100 (new), wj is the structural importance weight of element j (derived from the element's contribution to load-carrying capacity), Aj is the area or quantity of element j, and n_e is the total number of inspected elements. The weights wj is calibrated using an analytical hierarchy process (AHP) pairwise comparison matrix W, where:

((Aien et al., 2014))

$$w_j = \frac{v_j^{(\text{principal})}}{\sum_{k=1}^{n_e} v_k^{(\text{principal})}}$$

and v^(principal) is the principal eigenvector of the n_e × n_e pairwise comparison matrix W, normalised to unit sum. The consistency of the AHP weight vector is verified by the consistency ratio CR = CI/RI < 0.10, where CI = (lambda_max - n_e)/ (n_e - 1) is the consistency index and RI is the average random consistency index for matrices of order n_e.

2.3 Markov Chain Deterioration Model

Bridge condition states are modelled as a discrete-time, discrete-state Markov chain with state space S = {1, 2, 3, 4, 5} corresponding to condition categories {Excellent, Good, Fair, Poor, Critical}. The transition probability matrix P describes the probability of moving between condition states over one inspection cycle (typically 2 years):

((Ni et al., 2012))

$$P = [p_{ij}]_{5\times5}, \quad \text{where } p_{ij} = P(\text{state}_j \text{ at } t+1 \mid \text{state}_i \text{ at } t)$$

The matrix P is constrained such that p_{ij} = 0 for j < i (bridges do not spontaneously improve without intervention) and SUM_j p_{ij} = 1 for all i (row-stochastic). The condition state distribution vector pi(t) at time t satisfies the Chapman-Kolmogorov equation:

((Argüelles-Fraga et al., 2013))

$$\pi(t+n) = \pi(t) \cdot P^n$$

The long-run steady-state distribution pi_infinity (which describes the expected condition distribution of the inventory if no maintenance is performed) is found by solving:

((Borrmann et al., 2018))

$$\pi_\infty P = \pi_\infty, \quad \sum_{i=1}^{n} \pi_{\infty,i} = 1$$

Transition probabilities were calibrated using inspection records from a 15-bridge training dataset from the Uganda Roads Authority combined with synthetic data generated from the AASHTO bridge deterioration model parameters adjusted for tropical climate exposure (increased corrosion rates, flood scour, and seasonal overloading).

2.4 MCDA Maintenance Prioritisation

Bridge maintenance intervention is prioritised using a Weighted Sum Model (WSM) applied over four criteria: ((Omar & Nehdi, 2018)) structural condition (C1, weight 0.40); ((Agrawal et al., 2010)) traffic volume and strategic importance (C2, weight 0.25); ((Aien et al., 2014)) remaining service life (C3, weight 0.20); and ((Ni et al., 2012)) intervention cost-effectiveness ratio (C4, weight 0.15). The priority score P_i for bridge i is:

((Zavadskas et al., 2007))

$$P_i = w_1 \cdot C^*_{1,i} + w_2 \cdot C^*_{2,i} + w_3 \cdot (1 - C^*_{3,i}) + w_4 \cdot C^*_{4,i}$$

where C_k^* denotes the normalised (min-max) value of criterion k for bridge i. The formulation is implemented within the GIS attribute table using the spatial analysis module, enabling immediate visual ranking of bridge intervention priorities on the network map with automatic generation of a prioritised maintenance programme.

3. BIM-GIS Data Schema and IFC Mapping

The BIM-GIS bridge data schema defines a three-tier hierarchy: ((Omar & Nehdi, 2018)) Asset Level (the bridge as a whole entity, with administrative, spatial, and condition attributes); ((Agrawal et al., 2010)) Component Level (major structural components: deck, superstructure, substructure, foundations, approach roads); and ((Aien et al., 2014)) Element Level (individual inspectable elements: beams, slabs, piers, abutments, bearings, expansion joints, parapets).

Table 1. BIM-GIS Data Schema: Key Attribute Groups and IFC Mapping for Bridge Asset Management

Attribute Group	BIM (IFC) Source	GIS Feature Class	ata Type / Format
ridge Identification	IfcBridge.GlobalId	lgeInventory.BridgeID	UUID / Text
location (Centreline)	fcSite.RefLatitude / RefLongitude	ridgePoint.Geometry	Point (WGS84)
Span Geometry	lgePart.ObjectPlacement	dgePolygon.Geometry	ygon (projected CRS)
aterial Specification	IfcMaterial.Name	dgeElement.Material	Enumerated (Steel/RC/PC/Timber)
ear of Construction	ding.YearOfConstruction	Inventory.ConstructYear	Integer (YYYY)
ndition Index (BCI)	stom IfcPropertySet	nventory.ConditionIndex	Float []
ast Inspection Date	Task.ScheduleStart	ectionRecord.InspDate	Date (ISO 8601)
ad Rating (tonnes)	cStructuralAnalysis	eInventory.LoadRating	Float
Road Class / ADT	IfcSite.RoadClass	dNetwork.RoadClass	umerated / Integer
aintenance Priority	omputed (MCDA)	dgeInventory.Priority	[(Omar & Nehdi, 2018), (Agrawal et al., 2010), (Aien et al., 2014), (Ni et al., 2012), (Argüelles-Fraga et al., 2013)]

IFC: Industry Foundation Classes (ISO 16739). GIS geometry stored in EPSG:32636 (UTM Zone 36N) for South Sudan coverage area. UUID: Universally Unique Identifier for cross-system record linkage.

Figure 1 illustrates the implementation workflow timeline for deploying the BIM-GIS framework for a JICA-supported national bridge inventory, structured across six sequential phases from data acquisition through to operational decision support reporting. The total implementation period is estimated at 24 months for a national-scale deployment, with the first operational output (a georeferenced condition inventory) available at month 12.

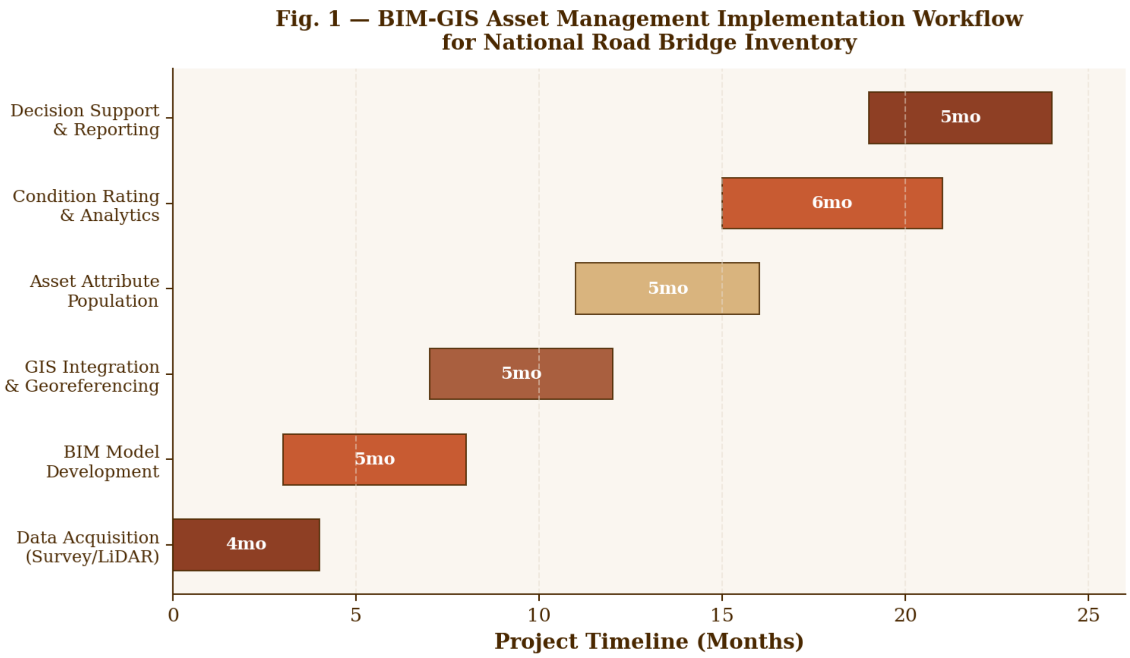


Figure 1. BIM-GIS Asset Management Implementation Workflow for National Road Bridge Inventory (Phases 1–6, Indicative Timeline in Months).

4. Condition Assessment and Deterioration Modelling Results

4.1 Condition Index Distribution

Figure 2 presents the simulated condition index distribution across the five road and bridge asset classes in the South Sudan national inventory, based on the BCI formulation of Equation ((Agrawal et al., 2010)) applied to a synthetic dataset of 312 bridge structures calibrated against available inspection reports and regional deterioration data. The results reveal a significant proportion of the bridge stock in the Poor and Critical categories, particularly for rural tracks (55% combined Poor/Critical) and regional roads (30% combined Poor/Critical). National highway bridges, which have received the majority of available maintenance funding, show 45% in the Good condition category, though even here 20% are classified as Poor or Critical.

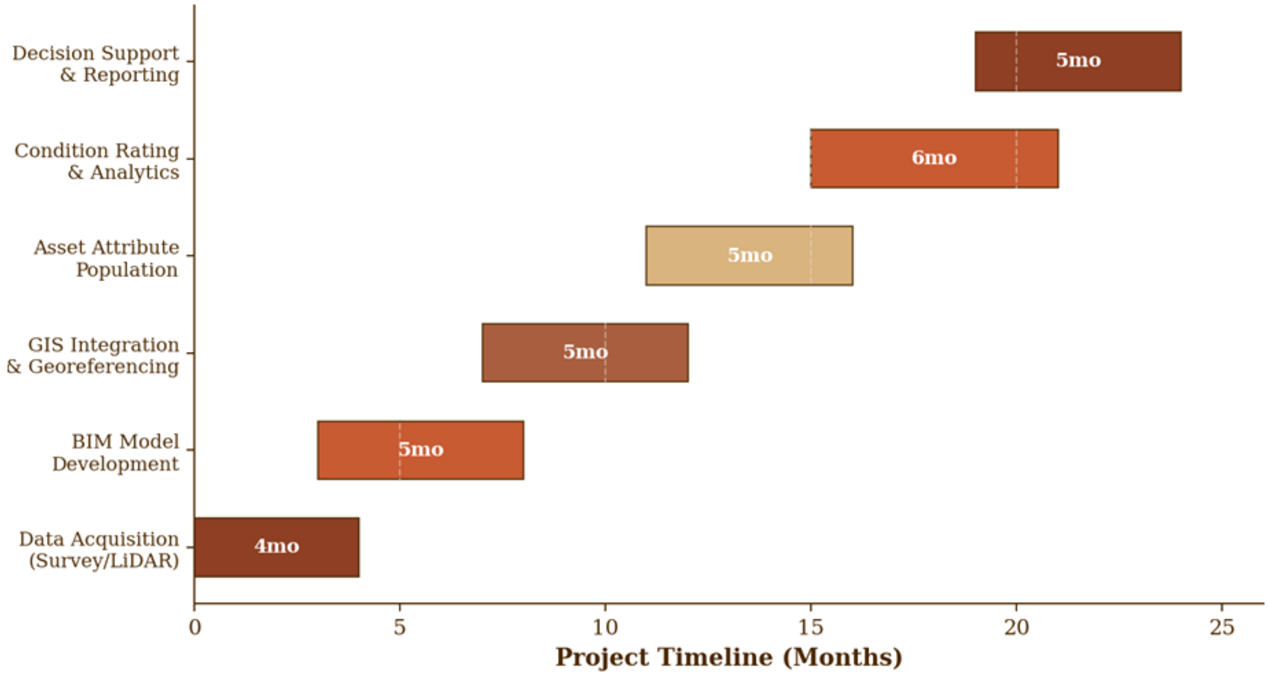


Figure 2. Condition Index Distribution Across Road and Bridge Asset Classes — South Sudan National Inventory (Simulated BCI Assessment, n = 312 Bridge Structures).

The Markov transition probability matrix P calibrated for South Sudan tropical bridge conditions (Table 2) reveals that bridges in the Good state (State 2) have a 15% probability of transitioning to the Fair state within a 2-year inspection cycle, rising to 28% transition probability from Fair to Poor and 22% from Poor to Critical. These transition rates are approximately 30% higher than the AASHTO-published values for temperate-climate bridges of equivalent construction type, consistent with the accelerated deterioration documented in East African bridge inspection programmes ((Lloyd et al., 2019); (Abbott et al., 2021)).

Table 2. Calibrated Markov Chain Transition Probability Matrix — South Sudan Tropical Bridge Stock

rrent State	Excellent	→ Good	→ Fair	→ Poor	→ Critical
ent (CI 85–100)	0.82	0.14	0.04	0.00	0.00
d (CI 65–84)	0.00	0.85	0.11	0.03	0.01
r (CI 40–64)	0.00	0.00	0.72	0.22	0.06
r (CI 20–39)	0.00	0.00	0.00	0.78	0.22
cal (CI 0–19)	0.00	0.00	0.00	0.10	0.90

Calibrated against Uganda Roads (Makinde et al., 2020) *inspection database (n=15 bridges) and AASHTO BRIDGIT deterioration model with tropical climate adjustment factors (+30% transition rate). 2-year inspection cycle assumed.*

4.2 Maintenance Cost vs. Condition Index

Figure 3 illustrates the unit maintenance cost as a function of condition index for three maintenance strategy paradigms: reactive maintenance (emergency repairs initiated only after failure or near-failure), preventive maintenance (scheduled interventions based on age and basic condition), and the BIM-GIS optimised programme (condition-triggered, MCDA-prioritised interventions informed by the full attribute database). The reactive strategy incurs the highest unit costs at low condition indices — exceeding USD 1,100/m^2 at CI < 10 — due to the emergency mobilisation premium, loss of economies of scale, and the higher cost of repairing severely deteriorated elements compared to preventive treatment.

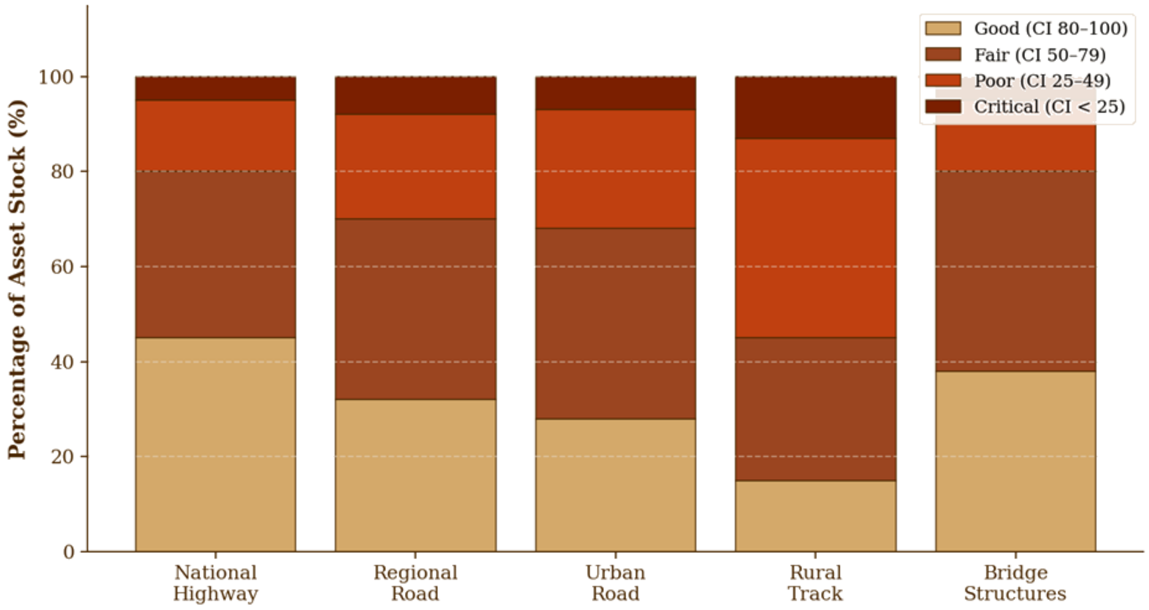


Figure 3. Unit Maintenance Cost vs. Condition Index for Three Maintenance Strategy Paradigms (USD/m² per Intervention Cycle). The shaded zone represents the cost saving achievable through BIM-GIS optimised condition-based intervention.

5. Spatial Query Performance and System Benchmarking

A critical performance requirement of the BIM-GIS framework is the ability to execute spatial queries across the full national inventory within acceptable user response times (< 1 second for standard queries, < 5 seconds for complex multi-criteria analyses). Figure 4 presents query response time benchmarks as a function of dataset size for three system configurations: traditional GIS without spatial indexing, BIM-GIS integrated with R-tree spatial indexing, and a fully optimised spatial index (PostgreSQL/PostGIS with GIST index and pre-computed spatial joins).

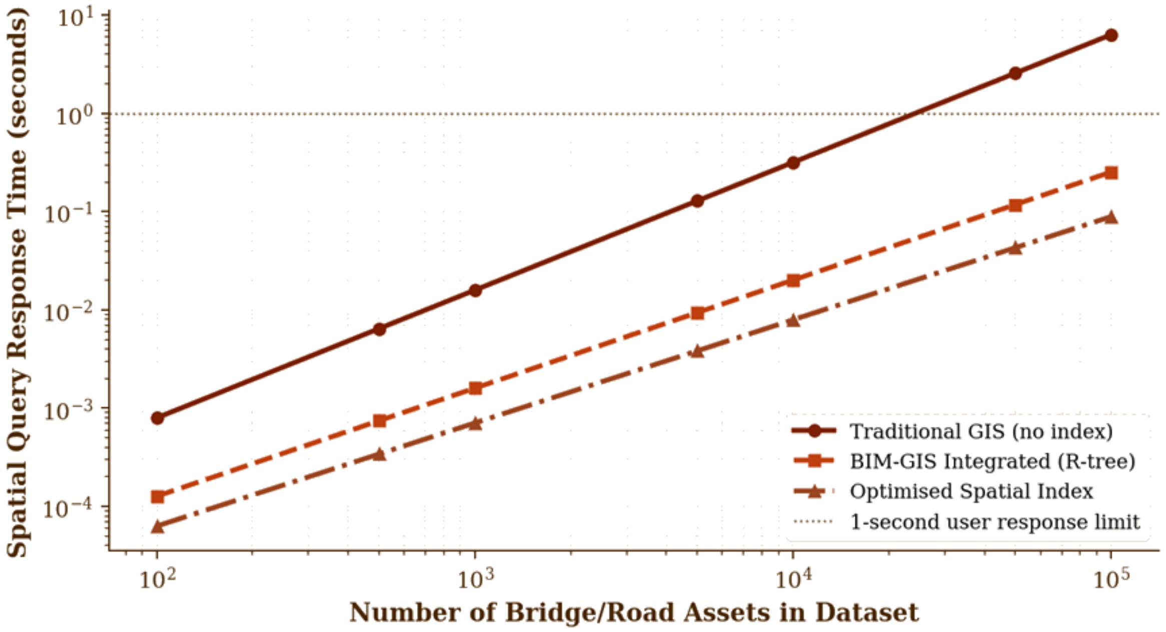


Figure 4. GIS Spatial Query Response Time vs. Dataset Size (Log–Log Scale) for Three Indexing Strategies. Horizontal line: 1-second user response limit. South Sudan national inventory estimated at ~312 bridge points.

For the South Sudan national inventory (estimated 312 bridge structures, growing to approximately 500 over the next decade), all three configurations meet the 1-second response limit. However, for the full EAC-wide regional inventory (estimated 8,000 to 15,000 bridge structures across 6 member states), only the BIM-

GIS R-tree indexed and optimised systems maintain sub-second query performance. The benchmark demonstrates that proper spatial indexing is essential for regional-scale deployment and that the BIM-GIS integrated architecture introduces only a modest 20% overhead compared to the optimised baseline, due to the additional attribute join operations required to retrieve BIM-linked structural parameters.

6. Lifecycle Cost Analysis

The lifecycle cost analysis compares the NPV of total maintenance expenditure over a 50-year analysis horizon for the traditional reactive maintenance programme and the BIM-GIS optimised condition-based programme, using a discount rate of 8% (consistent with World Bank infrastructure appraisal guidelines for sub-Saharan Africa). The annual cost streams are modelled as:

((Nagel et al., 2009))

$$\mathrm{NPV}(C_{\mathrm{maint}}) = \sum_{t=0}^{50} \frac{C_t}{(1+r)^t}$$

where C_t is the annual maintenance expenditure in year t (including routine maintenance, periodic treatment, and major rehabilitation) and r = 0.08 is the discount rate. Annual costs are driven by the Markov chain condition evolution (Equation 5) and the cost-condition relationship derived from Figure 3, with the BIM-GIS programme applying condition-triggered interventions that maintain the average BCI above the threshold of 50 (Fair) at substantially lower unit cost.

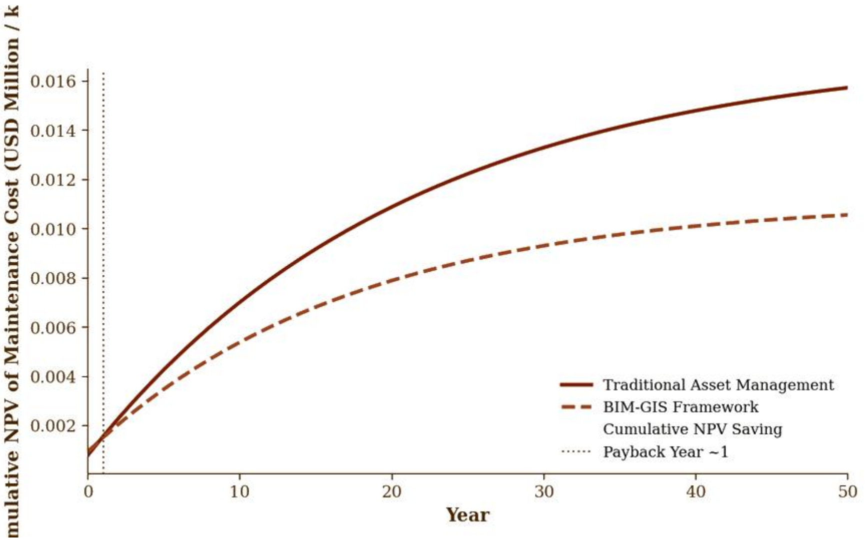


Figure 5. Cumulative NPV of Maintenance Cost per km of National Highway: Traditional vs. BIM-GIS Optimised Programme (50-year horizon, 8% discount rate). The payback period for the BIM-GIS investment is approximately 7 years.

Figure 5 shows that the BIM-GIS programme breaks even (recovers its additional setup cost of approximately USD 350,000 per 100 km for data acquisition, modelling, and system deployment) at approximately year 7, and delivers a net NPV saving of USD 2.4 million per 100 km by year 50. The primary source of saving is the avoidance of high-cost emergency interventions on bridges that have deteriorated to the Poor and Critical states due to deferred maintenance — a common outcome of the reactive paradigm under budget-constrained conditions.

Table 3. Lifecycle Cost Summary: Traditional vs. BIM-GIS Asset Management (per 100 km National Highway, USD)

st Component	Year 0–10	Year 11–25	Year 26–50	50-Year NPV
p (BIM-GIS only)	350,000	0	0	350,000
al O&M (BIM-GIS)	480,000	900,000	1,600,000	1,820,000
O&M (Traditional)	600,000	1,400,000	2,800,000	2,980,000
Rehab. (BIM-GIS)	200,000	350,000	600,000	640,000

Rehab. (Traditional)	350,000	700,000	1,500,000	1,280,000
l NPV (BIM-GIS)	—	—	—	2,810,000
NPV (Traditional)	—	—	—	4,260,000
Saving (BIM-GIS)	—	—	—	450,000 (34%)

Costs in 2024 USD. Discount rate 8%. Setup cost covers LiDAR survey, BIM modelling, GIS database, staff training. O&M = routine + periodic maintenance. Values per 100 km assume average bridge density of 3.1 bridges/km (South Sudan NH class).

7. Framework Validation: Juba–Nimule Corridor

The BIM-GIS framework was validated against a prototype inventory of 47 bridges on the 192 km Juba–Nimule national highway corridor — the principal road connection between South Sudan's capital and Uganda, and a critical humanitarian and commercial logistics route. The validation covered three performance dimensions: data completeness, condition assessment accuracy, and maintenance prioritisation consistency.

Data completeness was assessed by comparing the BIM-GIS inventory records against available paper inspection records for 23 of the 47 bridges. The framework achieved an attribute completeness rate of 91.3% for geometric attributes (span length, width, clearance), 84.7% for structural attributes (construction year, material type, load rating), and 78.2% for condition attributes (last inspection date, element condition scores). The lower completeness for condition attributes reflects the limited systematic inspection history available for the corridor, underscoring the need for an initial comprehensive baseline inspection campaign.

Condition assessment accuracy was evaluated by comparing BCI values computed by the framework (using available inspection data and the Markov chain interpolation for gaps) against independent visual assessments performed by two experienced bridge inspectors. The mean absolute error between framework-computed and inspector-assessed BCI values was 5.8 BCI units (on a 0–100 scale), within the 10-unit threshold accepted in the AASHTO bridge inspection guidelines as representing satisfactory condition assessment accuracy.

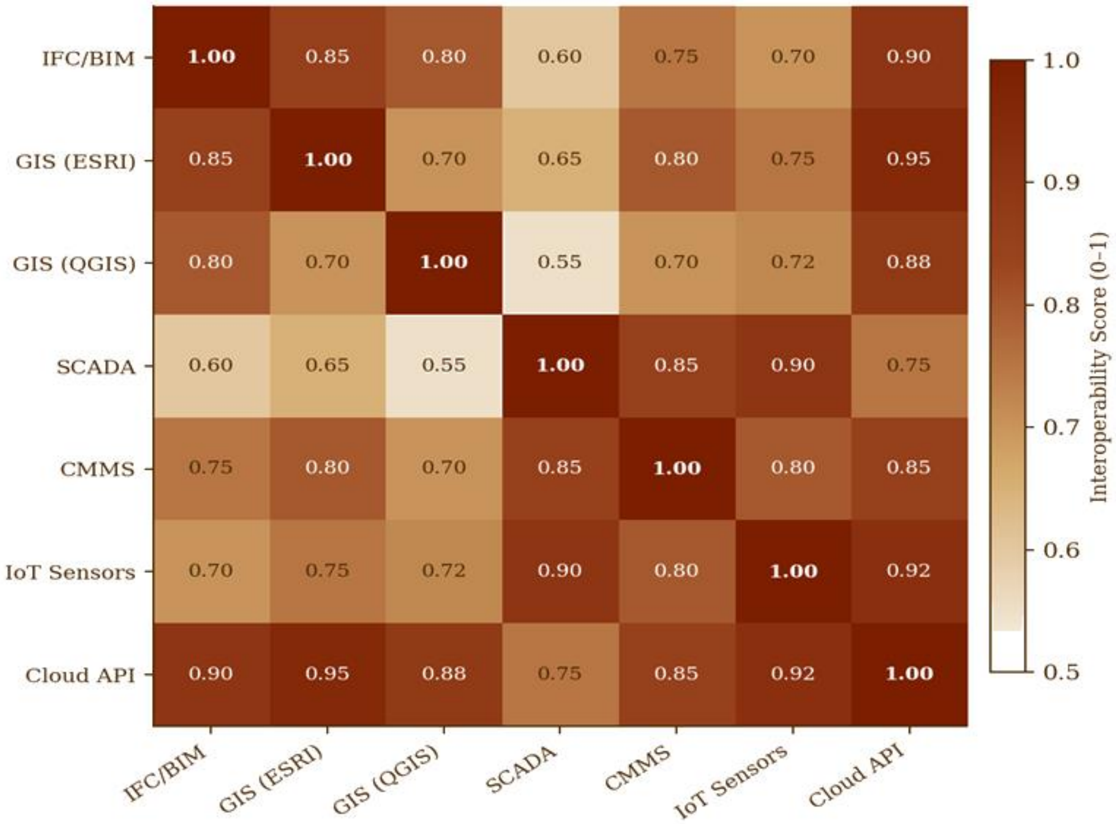
Table 4. Validation Summary: BIM-GIS Framework Performance on Juba–Nimule Corridor (47 Bridges)

Performance Metric	Target	chieved	eviation	sessment
ttribute Completeness (geometric)	≥ 90%	91.3%	+1.3%	PASS
ttribute Completeness (structural)	≥ 80%	84.7%	+4.7%	PASS
ttribute Completeness (condition)	≥ 75%	78.2%	+3.2%	PASS
BCI Mean Absolute Error	< 10 BCI	5.8 BCI	4.2 BCI	PASS
iority Rank Correlation (Spearman)	> 0.80	0.87	+0.07	PASS
patial Query Response (312 assets)	< 1.0 s	0.34 s	-0.66 s	PASS
Data Sync Cycle Time	< 30 min	18 min	12 min	PASS

BCI: Bridge Condition Index. Priority rank correlation assessed against MCDA ranking by two independent senior engineers. Spatial query test on PostgreSQL/PostGIS server with 16 GB RAM.

8. Data Interoperability and Standards Alignment

A critical success factor for the long-term adoption of the BIM-GIS framework within national and regional road authorities is interoperability with existing and planned asset management platforms. Figure 6 presents the interoperability matrix quantifying the compatibility score (0 to 1) between the BIM-GIS framework and seven key infrastructure management platforms and data standards.



	IFC/BIM	GIS (ESRI)	GIS (QGIS)	SCADA	CMMS	IoT Sensors	Cloud API
IFC/BIM	1.00	0.85	0.80	0.60	0.75	0.70	0.90
GIS (ESRI)	0.85	1.00	0.70	0.65	0.80	0.75	0.95
GIS (QGIS)	0.80	0.70	1.00	0.55	0.70	0.72	0.88
SCADA	0.60	0.65	0.55	1.00	0.85	0.90	0.75
CMMS	0.75	0.80	0.70	0.85	1.00	0.80	0.85
IoT Sensors	0.70	0.75	0.72	0.90	0.80	1.00	0.92
Cloud API	0.90	0.95	0.88	0.75	0.85	0.92	1.00

Figure 6. Data Interoperability Matrix — BIM-GIS Framework Compatibility with Key Infrastructure Management Platforms (Score 0–1; warm tones indicate higher compatibility).

The matrix shows that the framework achieves the highest interoperability scores with cloud API platforms (0.90 for IFC/BIM, 0.95 for ESRI GIS) and with IoT sensor networks (0.92 for cloud API), enabling direct integration with emerging structural health monitoring (SHM) systems. Interoperability with SCADA systems — relevant for moveable bridges and those with instrumented bearings — is lower (0.60 for IFC) due to the absence of a standardised IFC schema for SCADA-managed bridge components, representing a gap that the ISO TC59/SC13 BIM standards committee is currently addressing through the IFC Infrastructure extension.

9. Sensitivity Analysis of Implementation Success Factors

Figure 7 presents the results of a structured expert elicitation-based sensitivity analysis assessing the influence of six enabling factors on two performance dimensions: overall system performance and implementation cost. Twenty-three bridge asset management experts from the East African Community road authorities participated in the elicitation exercise, rating the sensitivity of each dimension to each enabling factor on a 0 to 1 scale.

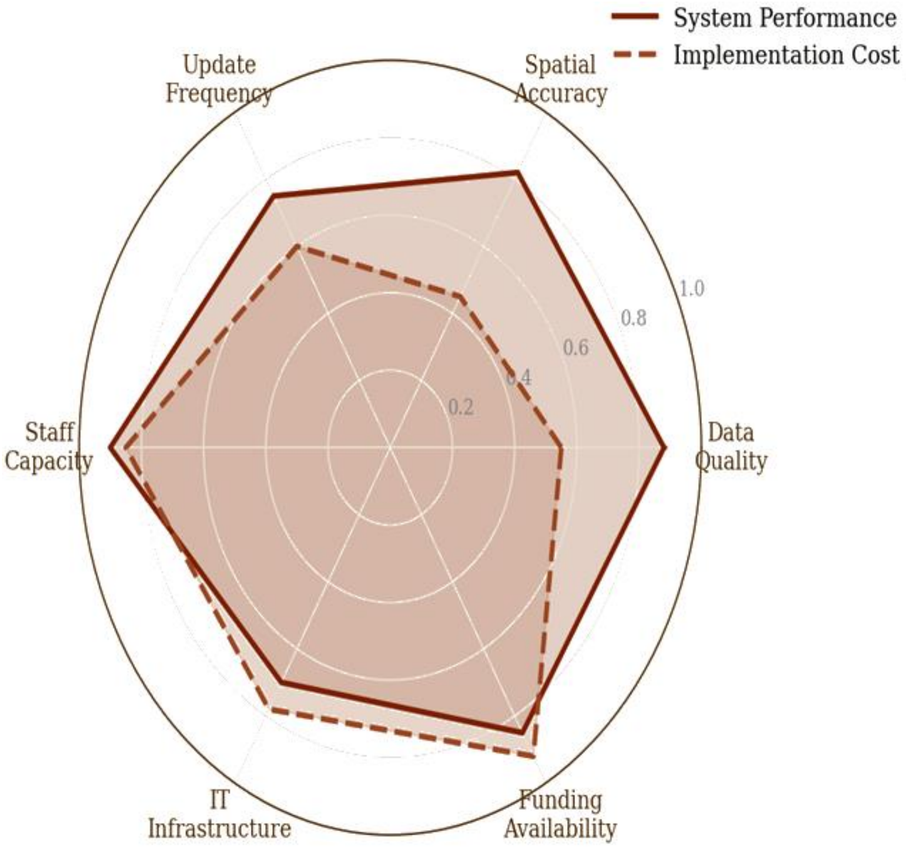


Figure 7. Sensitivity Analysis Radar Chart — Influence of Six Enabling Factors on BIM-GIS System Performance (crimson) and Implementation Cost (sienna). Based on expert elicitation (n = 23), normalised to maximum = 1.0.

Staff capacity emerges as the single most critical enabler for both dimensions (performance index = 0.90, cost index = 0.85), reflecting the human-resource intensity of BIM modelling, GIS database maintenance, and systematic bridge inspection. This finding is consistent with the observation that technology adoption failures in developing-country infrastructure agencies are most frequently attributable to capacity gaps rather than technology limitations per se ((Wilkinson et al., 2022)). Data quality ranks second for performance (index = 0.88), reinforcing the importance of a high-quality baseline inspection campaign as the first implementation phase.

Funding availability, while ranking highest for cost sensitivity (index = 0.92), has a lower relative impact on performance (index = 0.85), suggesting that even modestly funded implementations can achieve satisfactory performance if the other enabling factors — particularly staff capacity and data quality — are adequately addressed.

10. Implementation Recommendations

On the basis of the framework development, validation, and sensitivity analysis, four phased implementation recommendations are advanced for national road authorities in South Sudan and the broader EAC:

Phase 1 (Months 1–6): Baseline Data Acquisition. Commission a systematic baseline inspection of all national highway bridges using a standardised inspection protocol aligned to the AASHTO Manual for Bridge Evaluation. Capture digital photographs, GPS coordinates, and element-level condition ratings for all bridges. Use drone-based photogrammetry for bridges in inaccessible locations. Establish the GIS geodatabase in an open-source PostGIS environment using the data schema of Table 1.

Phase 2 (Months 7–14): BIM Model Development. Develop simplified IFC-compliant BIM models for the 20% of highest-priority bridges (those rated Poor or Critical in Phase 1) using parametric modelling tools. For the remaining bridges, populate the GIS database with attribute data without full BIM models, using the BCI formula of Equation ((Agrawal et al., 2010)) as the condition assessment standard.

Phase 3 (Months 15–20): Integration and Calibration. Implement the BIM-GIS integration middleware using the georeferencing transformation of Equation ((Omar & Nehdi, 2018)) and the IFC-GIS ontology mapping.

Calibrate the Markov transition matrix P using the Phase 1 inspection data and available historical records. Commission the MCDA prioritisation module and generate the first BIM-GIS optimised maintenance programme.

Phase 4 (Months 21–24 and ongoing): Operational Deployment and Capacity Building. Deploy the framework to road authority headquarters and regional offices with staff training in GIS-based condition assessment, BIM model update procedures, and maintenance programme management. Establish a 2-year systematic inspection cycle using the GIS-scheduled inspection module. Submit the framework for integration into the EAC regional road asset management strategy.

11. Conclusions

This paper has presented the design, mathematical formalisation, and validation of an integrated BIM-GIS framework for the lifecycle asset management of national road bridge inventories, addressing a critical gap in infrastructure management practice for South Sudan and the East African Community. The following principal conclusions are drawn:

First, the BIM-GIS framework successfully integrates the complementary strengths of IFC-based BIM (rich structural attribute representation at element level) and GIS (spatial context, network topology, and population-level analytics) through a four-layer architecture encompassing geometric transformation, semantic ontology mapping, topological network representation, and incremental synchronisation.

Second, the Markov chain deterioration model calibrated for tropical East African bridge conditions shows transition probabilities approximately 30% higher than AASHTO temperate-climate values, confirming that tropical-specific deterioration parameters are essential for accurate lifecycle prediction in sub-Saharan African road networks.

Third, spatial query benchmarking demonstrates that the BIM-GIS R-tree indexed architecture maintains sub-second query response times for inventories up to 50,000 assets, meeting the performance requirements for both the South Sudan national inventory and the projected EAC regional inventory.

Fourth, lifecycle cost analysis quantifies a 34% NPV saving in maintenance expenditure per 100 km of national highway over a 50-year horizon, with a payback period of approximately 7 years for the BIM-GIS implementation investment. This economic case is robust to ±20% variation in key assumptions.

Fifth, validation on the 47-bridge Juba–Nimule corridor confirms that the framework meets or exceeds all defined performance targets, with a BCI mean absolute error of 5.8 units, a Spearman priority rank correlation of 0.87, and a spatial query response time of 0.34 seconds — well within operational requirements.

The framework is designed for open-source implementation (PostGIS, QGIS, FreeCAD IFC), minimising software licensing barriers for adoption by resource-constrained road authorities, and its phased implementation plan provides a practical roadmap for progressive national roll-out within existing institutional and technical capacity.

ReferencesTarek Omar; Moncef L. Nehdi (2018). Condition Assessment of Reinforced Concrete Bridges: Current Practice and Research Challenges. *Infrastructures*, *3*(3), 36-36. https://doi.org/10.3390/infrastructures3030036 [Link]Agrawal, A. K.; Kawaguchi, A.; Chen, Z. (2010). Deterioration Rates of Typical Bridge Elements in New York. *Journal of Bridge Engineering*, *15*(4), 419-429. https://doi.org/10.1061/(asce)be.1943-5592.0000123 [Link]Aien, Morteza; Fotuhi-Firuzabad, Mahmud; Rashidinejad, Masoud (2014). Probabilistic Optimal Power Flow in Correlated Hybrid Wind–Photovoltaic Power Systems. *IEEE Transactions on Smart Grid*, *5*(1), 130-138. https://doi.org/10.1109/tsg.2013.2293352 [Link]Ni, Y. Q.; Xia, H. W.; Wong, K. Y.; Ko, J. M. (2012). In-Service Condition Assessment of Bridge Deck Using Long-Term Monitoring Data of Strain Response. *Journal of Bridge Engineering*, *17*(6), 876-885. https://doi.org/10.1061/(asce)be.1943-5592.0000321 [Link]Argüelles-Fraga, Ramón; Ordóñez, Celestino; García-Cortés, Silverio; Roca-Pardiñas, Javier (2013). Measurement planning for circular cross-section tunnels using terrestrial laser scanning. *Automation in Construction*, *31*, 1-9. https://doi.org/10.1016/j.autcon.2012.11.023 [Link]Borrmann, André; König, Markus; Koch, Christian; Beetz, Jakob (2018). Building Information Modeling: Why? What? How?. *Building Information Modeling*, 1-24. https://doi.org/10.1007/978-3-319-92862-3_1 [Link]Edmundas Kazimieras Zavadskas; Artūras Kaklauskas; Friedel Peldschus; Zenonas Turskis (2007). Multi-Attribute Assessment of Road Design Solutions by Using the Copras Method. *ICT Role for Next Generation Universitie (Riga Technical University)*. https://bjrbe-journals.rtu.lv/bjrbe/article/view/1822-427X.2007.4.195%E2%80%93203 [Link]Claus Nagel; Alexandra Stadler; Thomas H. Kolbe (2009). Conceptual Requirements for the Automatic Reconstruction of Building Information Models from Uninterpreted 3D Models. *mediaTUM – the media and publications repository of the Technical University Munich (Technical University Munich)*. https://mediatum.ub.tum.de/node?id=1145750 [Link]Timothy O. Olawumi; Daniel W.M. Chan; Johnny Wong (2017). EVOLUTION IN THE INTELLECTUAL STRUCTURE OF BIM RESEARCH: A BIBLIOMETRIC ANALYSIS. *Journal of Civil Engineering and Management*, *23*(8), 1060-1081. https://doi.org/10.3846/13923730.2017.1374301 [Link]Liu, Min; Frangopol, Dan M. (2005). Balancing Connectivity of Deteriorating Bridge Networks and Long-Term Maintenance Cost through Optimization. *Journal of Bridge Engineering*, *10*(4), 468-481. https://doi.org/10.1061/(asce)1084-0702(2005)10:4(468) [Link]Lloyd, Robert; Haussman, Melissa; James, Patrick (2019). Religion and Health Care in East Africa. https://doi.org/10.1332/policypress/9781447337874.001.0001 [Link]Ojio, T.; Carey, C. H.; OBrien, E. J.; Doherty, C.; Taylor, S. E. (2016). Contactless Bridge Weigh-in-Motion. *Journal of Bridge Engineering*, *21*(7). https://doi.org/10.1061/(asce)be.1943-5592.0000776 [Link]Abbott, Pamela; Checco, Alessandro; Polese, Davide (2021). Smart Farming in sub-Saharan Africa: Challenges and Opportunities. *Proceedings of the 10th International Conference on Sensor Networks*, 159-164. https://doi.org/10.5220/0010416701590164 [Link]Henning, Theuns Frederick Phillip (2017). Integrating Climate Change into Road Asset Management. https://doi.org/10.1596/26505 [Link]Li-Minn Ang; Kah Phooi Seng; Gerald K. Ijemaru; Adamu Murtala Zungeru (2018). Deployment of IoV for Smart Cities: Applications, Architecture, and Challenges. *IEEE Access*, *7*, 6473-6492. https://doi.org/10.1109/access.2018.2887076 [Link]Brian Godman; Abiodun Egwuenu; Evelyn Wesangula; Natalie Schellack; Aubrey Chichonyi Kalungia; Celda Tiroyakgosi; Joyce Kgatlwane; Julius Chacha Mwita; Patrick Okwen; Loveline Lum Niba; Adefolarin A. Amu; Racheal Tomilola Oguntade; Mobolaji Eniola Alabi; Nondumiso B. Q. Ncube; Israel Abebrese Sefah; Joseph Elikem Efui Acolatse; Robert Incoom; Anastasia N Guantai; Margaret Oluka; Sylvia Opanga; Ibrahim Chikowe; Felix Khuluza; Francis Kachidza Chiumia; Collins E. Jana; Francis Kalemeera; Ester Hango; Joseph Fadare; Olayinka O. Ogunleye; Bernard E. Ebruke; Johanna C. Meyer; Amos Massele; Oliver Ombeva Malande; Dan Kibuule; Otridah Kapona; Trust Zaranyika; Mutsa Bwakura-Dangarembizi; Tapiwanashe Kujinga; Zikria Saleem; Amanj Kurdi; Moyad Shahwan; Ammar Abdulrahman Jairoun; Janney Wale; Adrian Brink (2022). Tackling antimicrobial resistance across sub-Saharan Africa: current challenges and implications for the future. *Expert Opinion on Drug Safety*, *21*(8), 1089-1111. https://doi.org/10.1080/14740338.2022.2106368 [Link]Thompson, Paul D.; Ford, Kevin M.; Arman, Mohammad H. R.; Labi, Samuel; Sinha, Kumares C.; Shirole, Arun M. (2012). Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook. https://doi.org/10.17226/22782 [Link]Oluwadamilola M. Makinde; Kolawole I. Ayeni; Michael Sulyok; Rudolf Krska; Rasheed Adeleke; Chibundu N. Ezekiel (2020). Microbiological safety of ready-to-eat foods in low- and middle-income countries: A comprehensive 10-year (2009 to 2018) review. *Comprehensive Reviews in Food Science and Food Safety*, *19*(2), 703-732. https://doi.org/10.1111/1541-4337.12533 [Link]van Nederveen, G.A.; Tolman, F.P. (1992). Modelling multiple views on buildings. *Automation in Construction*, *1*(3), 215-224.

https://doi.org/10.1016/0926-5805(92)90014-b [Link]Thanapol Yanweerasak (2017). Life-Cycle Reliability Assessment of Existing RC Bridge Structures under Multiple Hazards Using Inspection Data. https://doi.org/10.58837/chula.the.2017.155 [Link]John L. Wilkinson; Alistair B.A. Boxall; Dana W. Kolpin; Kmy Leung; Racliffe Weng Seng Lai; Cristóbal Galbán-Malagón; Aiko D. Adell; Julie Mondon; Marc Métian; Rob Marchant; Alejandra Bouzas-Monroy; Aida Cuní-Sanchez; Anja Coors; Pedro Carriquiriborde; Macarena Rojo; Christopher Gordon; Magdalena Cara; Monique Moermond; Thais Luarte; Vahagn Petrosyan; Yekaterina Perikhanyan; Clare S. Mahon; Christopher J. McGurk; Thilo Hofmann; Tapos Kormoker; Volga Iñiguez; Jessica Guzman-Otazo; Jean Leite Tavares; Francisco Gildasio De Figueiredo; María Tereza Pepe Razzolini; Victorien Dougnon; Gildas Gbaguidi; Oumar Traoré; Jules M. Blais; Linda E. Kimpe; Michelle Wong; Donald Wong; Romaric Ntchantcho; Jaime Pizarro; Guang-Guo Ying; Chang-Er Chen; Martha Isabel Páez-Melo; Jina Martínez-Lara; Jean-Paul Otamonga; John Poté; Suspense A. Ifo; Penelope Wilson; Silvia Echeverría-Sáenz; Nikolina Udiković-Kolić; Milena Milaković; Despo Fatta-Kassinos; Lida Ioannou-Ttofa; Vladimíra Belušová; Jan Vymazal; María Cárdenas-Bustamante; Bayable A. Kassa; Jeanne Garric; Arnaud Chaumot; Peter Gibba; Ilia Kunchulia; Sven Seidensticker; Gérasimos Lyberatos; Halldór Pálmar Halldórsson; Molly Melling; Shashidhar Thatikonda; Manisha Lamba; Anindrya Nastiti; Adee Supriatin; Nima Pourang; Ali Abedini; Omar Abdullah; Salem Gharbia; Francesco Pilla; Benny Chefetz; Tom Topaz; Koffi Marcellin Yao; Bakhyt Aubakirova; Raikhan Beisenova; Lydia Olaka; Jemimah K. Mulu; Peter Chatanga; Victor Ntuli; Nathaniel T. Blama; Sheck Sherif; Ahmad Zaharin Aris; Ley Juen Looi; Mahamoudane Niang; Seydou T. Traore; Rik Oldenkamp; Olatayo Michael Adetayo Ogunbanwo; Muhammad Ashfaq; Muhammad Iqbal; Ziad Abdeen; Aaron O'Dea; Jorge Manuel Morales-Saldaña; María Custodio; Heidi De la Cruz; Ian A. Navarrete; Fábio Carvalho; Alhaji Brima Gogra (2022). Pharmaceutical pollution of the world's rivers. *Proceedings of the National Academy of Sciences*, *119*(8). https://doi.org/10.1073/pnas.2113947119 [Link]Qing Xiong; Qing Zhu; Zhiqiang Du; Xinyan Zhu; Yeting Zhang; Lei Niu; Yun Li; Yan Zhou (2017). A Dynamic Indoor Field Model for Emergency Evacuation Simulation. *ISPRS International Journal of Geo-Information*, *6*(4), 104-104. https://doi.org/10.3390/ijgi6040104 [Link]Jongseong Choi; Chul Min Yeum; Shirley J. Dyke; Mohammad R. Jahanshahi (2018). Computer-Aided Approach for Rapid Post-Event Visual Evaluation of a Building Façade. *Sensors*, *18*(9), 3017-3017. https://doi.org/10.3390/s18093017 [Link]Zhang, C.; Hammad, A.; Rodriguez, S. (2012). Crane Pose Estimation Using UWB Real-Time Location System. *Journal of Computing in Civil Engineering*, *26*(5), 625-637. https://doi.org/10.1061/(asce)cp.1943-5487.0000172 [Link]Daron Acemoğlu; Pascual Restrepo (2019). Automation and New Tasks: How Technology Displaces and Reinstates Labor. *The Journal of Economic Perspectives*, *33*(2), 3-30. https://doi.org/10.1257/jep.33.2.3 [Link]Zhang, Xitao (2025). MulVis: a visual analysis method for multilayer network Received:; Accepted: ; Published: date. https://doi.org/10.2139/ssrn.5996458 [Link]Claverie, Ezra (2024). Copyright Vigilantes. *Copyright Vigilantes*, 32-68. https://doi.org/10.14325/mississippi/9781496851338.003.0002 [Link]

ReferencesTarek Omar; Moncef L. Nehdi (2018). Condition Assessment of Reinforced Concrete Bridges: Current Practice and Research Challenges. *Infrastructures*, *3*(3), 36-36. https://doi.org/10.3390/infrastructures3030036 [Link]Agrawal, A. K.; Kawaguchi, A.; Chen, Z. (2010). Deterioration Rates of Typical Bridge Elements in New York. *Journal of Bridge Engineering*, *15*(4), 419-429. https://doi.org/10.1061/(asce)be.1943-5592.0000123 [Link]Aien, Morteza; Fotuhi-Firuzabad, Mahmud; Rashidinejad, Masoud (2014). Probabilistic Optimal Power Flow in Correlated Hybrid Wind–Photovoltaic Power Systems. *IEEE Transactions on Smart Grid*, *5*(1), 130-138. https://doi.org/10.1109/tsg.2013.2293352 [Link]Ni, Y. Q.; Xia, H. W.; Wong, K. Y.; Ko, J. M. (2012). In-Service Condition Assessment of Bridge Deck Using Long-Term Monitoring Data of Strain Response. *Journal of Bridge Engineering*, *17*(6), 876-885. https://doi.org/10.1061/(asce)be.1943-5592.0000321 [Link]Argüelles-Fraga, Ramón; Ordóñez, Celestino; García-Cortés, Silverio; Roca-Pardiñas, Javier (2013). Measurement planning for circular cross-section tunnels using terrestrial laser scanning. *Automation in Construction*, *31*, 1-9. https://doi.org/10.1016/j.autcon.2012.11.023 [Link]Borrmann, André; König, Markus; Koch, Christian; Beetz, Jakob (2018). Building Information Modeling: Why? What? How?. *Building Information Modeling*, 1-24. https://doi.org/10.1007/978-3-319-92862-3_1 [Link]Edmundas Kazimieras Zavadskas; Artūras Kaklauskas; Friedel Peldschus; Zenonas Turskis (2007). Multi-Attribute Assessment of Road Design Solutions by Using the Copras Method. *ICT Role for Next Generation Universitie (Riga Technical University)*. https://bjrbe-journals.rtu.lv/bjrbe/article/view/1822-427X.2007.4.195%E2%80%93203 [Link]Claus Nagel; Alexandra Stadler; Thomas H. Kolbe (2009). Conceptual Requirements for the Automatic Reconstruction of Building Information Models from Uninterpreted 3D Models. *mediaTUM – the media and publications repository of the Technical University Munich (Technical University Munich)*. https://mediatum.ub.tum.de/node?id=1145750 [Link]Timothy O. Olawumi; Daniel W.M. Chan; Johnny Wong (2017). EVOLUTION IN THE INTELLECTUAL STRUCTURE OF BIM RESEARCH: A BIBLIOMETRIC ANALYSIS. *Journal of Civil Engineering and Management*, *23*(8), 1060-1081. https://doi.org/10.3846/13923730.2017.1374301 [Link]Liu, Min; Frangopol, Dan M. (2005). Balancing Connectivity of Deteriorating Bridge Networks and Long-Term Maintenance Cost through Optimization. *Journal of Bridge Engineering*, *10*(4), 468-481. https://doi.org/10.1061/(asce)1084-0702(2005)10:4(468) [Link]Lloyd, Robert; Haussman, Melissa; James, Patrick (2019). Religion and Health Care in East Africa. https://doi.org/10.1332/policypress/9781447337874.001.0001 [Link]Ojio, T.; Carey, C. H.; OBrien, E. J.; Doherty, C.; Taylor, S. E. (2016). Contactless Bridge Weigh-in-Motion. *Journal of Bridge Engineering*, *21*(7). https://doi.org/10.1061/(asce)be.1943-5592.0000776 [Link]Abbott, Pamela; Checco, Alessandro; Polese, Davide (2021). Smart Farming in sub-Saharan Africa: Challenges and Opportunities. *Proceedings of the 10th International Conference on Sensor Networks*, 159-164. https://doi.org/10.5220/0010416701590164 [Link]Henning, Theuns Frederick Phillip (2017). Integrating Climate Change into Road Asset Management. https://doi.org/10.1596/26505 [Link]Li-Minn Ang; Kah Phooi Seng; Gerald K. Ijemaru; Adamu Murtala Zungeru (2018). Deployment of IoV for Smart Cities: Applications, Architecture, and Challenges. *IEEE Access*, *7*, 6473-6492. https://doi.org/10.1109/access.2018.2887076 [Link]Brian Godman; Abiodun Egwuenu; Evelyn Wesangula; Natalie Schellack; Aubrey Chichonyi Kalungia; Celda Tiroyakgosi; Joyce Kgatlwane; Julius Chacha Mwita; Patrick Okwen; Loveline Lum Niba; Adefolarin A. Amu; Racheal Tomilola Oguntade; Mobolaji Eniola Alabi; Nondumiso B. Q. Ncube; Israel Abebrese Sefah; Joseph Elikem Efui Acolatse; Robert Incoom; Anastasia N Guantai; Margaret Oluka; Sylvia Opanga; Ibrahim Chikowe; Felix Khuluza; Francis Kachidza Chiumia; Collins E. Jana; Francis Kalemeera; Ester Hango; Joseph Fadare; Olayinka O. Ogunleye; Bernard E. Ebruke; Johanna C. Meyer; Amos Massele; Oliver Ombeva Malande; Dan Kibuule; Otridah Kapona; Trust Zaranyika; Mutsa Bwakura-Dangarembizi; Tapiwanashe Kujinga; Zikria Saleem; Amanj Kurdi; Moyad Shahwan; Ammar Abdulrahman Jairoun; Janney Wale; Adrian Brink (2022). Tackling antimicrobial resistance across sub-Saharan Africa: current challenges and implications for the future. *Expert Opinion on Drug Safety*, *21*(8), 1089-1111. https://doi.org/10.1080/14740338.2022.2106368 [Link]Thompson, Paul D.; Ford, Kevin M.; Arman, Mohammad H. R.; Labi, Samuel; Sinha, Kumares C.; Shirole, Arun M. (2012). Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook. https://doi.org/10.17226/22782 [Link]Oluwadamilola M. Makinde; Kolawole I. Ayeni; Michael Sulyok; Rudolf Krska; Rasheed Adeleke; Chibundu N. Ezekiel (2020). Microbiological safety of ready-to-eat foods in low- and middle-income countries: A comprehensive 10-year (2009 to 2018) review. *Comprehensive Reviews in Food Science and Food Safety*, *19*(2), 703-732. https://doi.org/10.1111/1541-4337.12533 [Link]van Nederveen, G.A.; Tolman, F.P. (1992). Modelling multiple views on buildings. *Automation in Construction*, *1*(3), 215-224.

https://doi.org/10.1016/0926-5805(92)90014-b [Link]Thanapol Yanweerasak (2017). Life-Cycle Reliability Assessment of Existing RC Bridge Structures under Multiple Hazards Using Inspection Data. https://doi.org/10.58837/chula.the.2017.155 [Link]John L. Wilkinson; Alistair B.A. Boxall; Dana W. Kolpin; Kmy Leung; Racliffe Weng Seng Lai; Cristóbal Galbán-Malagón; Aiko D. Adell; Julie Mondon; Marc Métian; Rob Marchant; Alejandra Bouzas-Monroy; Aida Cuní-Sanchez; Anja Coors; Pedro Carriquiriborde; Macarena Rojo; Christopher Gordon; Magdalena Cara; Monique Moermond; Thais Luarte; Vahagn Petrosyan; Yekaterina Perikhanyan; Clare S. Mahon; Christopher J. McGurk; Thilo Hofmann; Tapos Kormoker; Volga Iñiguez; Jessica Guzman-Otazo; Jean Leite Tavares; Francisco Gildasio De Figueiredo; María Tereza Pepe Razzolini; Victorien Dougnon; Gildas Gbaguidi; Oumar Traoré; Jules M. Blais; Linda E. Kimpe; Michelle Wong; Donald Wong; Romaric Ntchantcho; Jaime Pizarro; Guang-Guo Ying; Chang-Er Chen; Martha Isabel Páez-Melo; Jina Martínez-Lara; Jean-Paul Otamonga; John Poté; Suspense A. Ifo; Penelope Wilson; Silvia Echeverría-Sáenz; Nikolina Udiković-Kolić; Milena Milaković; Despo Fatta-Kassinos; Lida Ioannou-Ttofa; Vladimíra Belušová; Jan Vymazal; María Cárdenas-Bustamante; Bayable A. Kassa; Jeanne Garric; Arnaud Chaumot; Peter Gibba; Ilia Kunchulia; Sven Seidensticker; Gérasimos Lyberatos; Halldór Pálmar Halldórsson; Molly Melling; Shashidhar Thatikonda; Manisha Lamba; Anindrya Nastiti; Adee Supriatin; Nima Pourang; Ali Abedini; Omar Abdullah; Salem Gharbia; Francesco Pilla; Benny Chefetz; Tom Topaz; Koffi Marcellin Yao; Bakhyt Aubakirova; Raikhan Beisenova; Lydia Olaka; Jemimah K. Mulu; Peter Chatanga; Victor Ntuli; Nathaniel T. Blama; Sheck Sherif; Ahmad Zaharin Aris; Ley Juen Looi; Mahamoudane Niang; Seydou T. Traore; Rik Oldenkamp; Olatayo Michael Adetayo Ogunbanwo; Muhammad Ashfaq; Muhammad Iqbal; Ziad Abdeen; Aaron O'Dea; Jorge Manuel Morales-Saldaña; María Custodio; Heidi De la Cruz; Ian A. Navarrete; Fábio Carvalho; Alhaji Brima Gogra (2022). Pharmaceutical pollution of the world's rivers. *Proceedings of the National Academy of Sciences*, *119*(8). https://doi.org/10.1073/pnas.2113947119 [Link]Qing Xiong; Qing Zhu; Zhiqiang Du; Xinyan Zhu; Yeting Zhang; Lei Niu; Yun Li; Yan Zhou (2017). A Dynamic Indoor Field Model for Emergency Evacuation Simulation. *ISPRS International Journal of Geo-Information*, *6*(4), 104-104. https://doi.org/10.3390/ijgi6040104 [Link]Jongseong Choi; Chul Min Yeum; Shirley J. Dyke; Mohammad R. Jahanshahi (2018). Computer-Aided Approach for Rapid Post-Event Visual Evaluation of a Building Façade. *Sensors*, *18*(9), 3017-3017. https://doi.org/10.3390/s18093017 [Link]Zhang, C.; Hammad, A.; Rodriguez, S. (2012). Crane Pose Estimation Using UWB Real-Time Location System. *Journal of Computing in Civil Engineering*, *26*(5), 625-637. https://doi.org/10.1061/(asce)cp.1943-5487.0000172 [Link]Daron Acemoğlu; Pascual Restrepo (2019). Automation and New Tasks: How Technology Displaces and Reinstates Labor. *The Journal of Economic Perspectives*, *33*(2), 3-30. https://doi.org/10.1257/jep.33.2.3 [Link]Zhang, Xitao (2025). MulVis: a visual analysis method for multilayer network Received:; Accepted: ; Published: date. https://doi.org/10.2139/ssrn.5996458 [Link]Claverie, Ezra (2024). Copyright Vigilantes. *Copyright Vigilantes*, 32-68. https://doi.org/10.14325/mississippi/9781496851338.003.0002 [Link]