ENHANCEMENTS IN BRIDGE MANAGEMENT INCORPORATING FUTURISTIC TECHNOLOGIES

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INTRODUCTION

Bridges are vital links in any road network. It is of vital importance to maintain these links. A loss of a bridge can paralyze the overall performance of the road network and cause excessive public and private loss.

Bridges within the network need to be managed in a way that ensures their uninterrupted performance throughout their design life.

Many bridges are affected by deterioration impacts that may occur due to natural disasters, the increase in traffic volumes, weather conditions, and/or material and strength degradation (i. e., corrosion, soil scour, and others), which may have a significant reduction on the structural capacity of the bridge or may urgently require action. [1, 2, 3]

Infrastructure around the world is facing all these problems. For bridges, the situation is compounded by aging, lack of funding for much-needed interventions and sometimes apathy of the owners to maintain the bridge populations.

In this scenario, bridge management teams around the world are faced with the challenge to endure user safety and manage the sustainability of bridges.

Bridge management teams are driven back to the drawing board with the aim to incorporate better efficiency in management principles. They endeavour to bring in innovations that will address the problems in a cost-effective manner.

Bridge management needs to focus on the optimization of fund allocation to address the deteriorating condition of bridges ensuring that sustainability is maintained without compromising the economic potential of the area.

Till recently, most of the decision-making was based on visual inspection by bridge inspection teams. This led to judgment-based conclusions which were used to decide the optimization of fund allocation. This at times may not be reliable because some damages are difficult to detect, quantify visually, or are subject to human interpretation. [4,13]

The search to supplement this system of reaching conclusions brought Structural Health Monitoring [SHM] to the forefront.

Innovations in SHM is playing a significant role in recent times because of their potential to capture real-time performance data, which helps in the reduction of maintenance costs resulting in an overall increase in the reliability of bridge structures.

The focus of SHM is on damage detection which causes distress leading to the deterioration of structures.

SHM applies real-time monitoring under live loads and applies digital techniques for analysis. Using the SHM, it is possible to monitor the bridge for the short term periodically.

It is possible to monitor the response of the bridge structure which reveals modifications to the material and structural properties.

SHM is important for maintenance planning to find a cost-effective solution to reduce costs and extend the life of critical assets like bridges. SHM has been widely used in many bridge structures around the world.

For this reason, a lot of bridge SHM data is available for analysis. This has facilitated the evolution of tools that have been developed to help government agencies manage bridges efficiently. [4, 5, 6, 7, 8, 9, 13]

There is an abundance in the variety of sensors, which are useful to assess the real-time behaviour of the structures.

Historically, monitoring devices were contact based but recent innovations render it possible to remotely monitor the structures.

The evolution of algorithms, to link SHM data to modification in a cause matrix, provides much-needed solutions. SHM enables bridge management to move the decision-making process to rely on real-time performance-based data.

The research to balance sustainability and economic growth has been the next focus research area of bridge management.

In the **Bridge Management System** [BMS], the key function of fund allocation optimization must be achieved by maintaining the balance between the preservation of sustainable environment and management of the economic benefits due to the prolonged life span of bridge structures.

It should ensure that the sustainability parameters are maintained during the life cycle of any bridge including the period of maintenance, rehabilitation, restoration, and replacement.

Sustainability management during the design and maintenance of infrastructure is ensured with the help of **Life-Cycle Cost Analysis** [LCCA].

The purpose of a Life-Cycle Cost Analysis [LCCA] is to estimate the overall financial cost of project alternatives and to select the design that ensures that the facility will provide the lowest cost of ownership consistent with its quality and function.

LCCA becomes more realistic if the benefits resulting from social, economic, and environmental parameters are also accounted for.

Unified Bridge Management System (UBMS) Analytics considers this management of the balance between sustainability and economics as an important focus area. This ensures the provision of a sustainable life cycle in the most cost-effective manner for the bridges. [10,11,12,13, 17, 21]

Bridge Management System is designed to manage a network of bridges under the constraints of limited budget and resources.

Many BMS have been assessing bridge conditions, modelling future deterioration behaviour, and the decisions making processes of fund allocation optimization, sustainability, economy for maintenance, and rehabilitation.

Various researchers have dealt with individual aspects of bridge management system components such as deterioration models, condition assessment, and life cycle cost analysis [20] that are critical to the optimization of funds.

To perform these functions, AASHTO and other similar guidelines for bridge management suggest that BMS should include the following components: data storage, cost model, deterioration models and optimization models.

Research is focused to evolve a comprehensive system using algorithms to optimize fund allocation, manage the life cycle costs and make it sustainable.

The system represents tools for decision-makers in optimizing bridge maintenance plans and repair strategies over a number of years within a budget limit and other constraints so that feasible and practical plans can be determined and to develop new strategies for managing public infrastructure assets in a way that ensures long-term sustainability under constrained budgets.

The analytics module within Unified Bridge Management System (UBMS) provides a possible solution by ensuring the Sustainability of bridge infrastructure without compromising the economic growth potential of the region in which the bridge is located.

Integration of SHM with UBMS offers data based on realistic observations, delinking it from any bias or judgment. [13, 18]

This integration results in a procedure to modify the Cause matrix whenever the Performance is observed to have decreased.

This ensures a Performance-based decision-making process within UBMS. This when combined, with the usage of Socio-Economic parameters collected in the inventory module of UBMS, ensures maintaining the balance between Sustainability and economic growth. Analytics within UBMS is a potent tool to address the present scenario.

STRUCTURAL HEALTH MONITORING [SHM]– REAL-TIME ANALYSIS OF BRIDGES UNDER LIVE LOAD

Essential information for bridge management is related to the construction and condition of the bridge. The inventory and inspection of bridges on the network is the first step in the process of compiling this crucial data.

The bridge inspection engineer must gather and compile information regarding various types of distress, details of locational, extent, and degree of severity during the inspection of the bridge structure.

Different elements of the bridge exhibit various distress. Normally, failure starts at the element which shows the maximum distress. Such elements tend to fail first. This results in the cascading effect, and ultimately in the failure of the entire bridge.

Location, intensity, and degree of distress are therefore crucial from the perspective of bridge maintenance and management. [1, 12, 13,18]

The Bridge Inspector can focus on identifying the most severely distressed elements after determining the geospatial locational data, the extent, and the severity of the distress in the element.

It is essential to identify the elements that are severely distressed before moving forward with the deployment of SHM. The elements displaying severe distress are subjected to short-term SHM. The performance data is recorded for all such elements.

To record the variation in the performance of such distressed elements under live loads, subsequently, periodic short-term SHM is used.

Short-term monitoring can be carried out using a variety of methodologies and sensors. The cause of the distress will determine the kind of sensors to deploy, the methods, and the parameters to be monitored.

The reason for distress is defined by three main processes as defined by EN 1504[19, 13]

Two types of SHM are envisaged to achieve the required objectives:

1. **Remote or No contact SHM:** A system where the parameters such as vibration signature, amplitude, acceleration, frequency, and strain are captured by technology that does not require any physical contact with the bridge.
2. **Contact SHM:** System wherein major strain, stress, linear displacement equations, inclination, vibration, frequency, acceleration, and corrosion potential are measured by sensors [Strain Gauges, Linear Variable Differential Transformer (LVDT), Tilt Meter, Inclinometer Sensors, Acoustic Emission Sensors (AE), Fibre Optic Sensors, Corrosion Sensors, Accelerometer] in close contact with various desired components of bridges.

A brief indicative list of sensors, see Figure 1, that can be used, and their limitations are enumerated below. The limitations can be overcome and are indicative. Many other sensors can be used for short-term SHM. [7, 8, 9, 13]

Close Contact and No Contact SHM systems results will show variations in performance if any occur.

Changes in performance imply changes in distress. It is well-known that an increment in the degree and extent of the distress will result in a decrement in the performance of the bridge element.

This behaviour fact is considered for integrating the data of SHM within UBMS.

A data-gathering device connects sensors remotely or by a wire. Measured data is converted to digital form in an AD converter and transmitted wirelessly via a Bluetooth module and Access Point (AP).

The gathered information is kept on a computer's hard drive or in a storage device's (SD) memory. A signal sender from a computer synchronizes the time of a data acquisition device.

Sr.No.	Sensors	Uses	Limitations
1.	Strain Gauges	To measure strain, to measure resultant stress.	1.Require the application surface to be finished and clean. 2. Sensitive to overload
2.	Accelerometer	For measuring acceleration force, vibration of the bridge.	1. Does not measure constant velocity.
3.	Temperature Sensors	To measures temperature of its environment.	1. Difficult to verify. 2. Non-linear. 3.Recalibration is difficult.
4.	VIDUR & VEDA	Used for Photonic System for vibration and condition monitoring of Structures.	-----

Figure 1: Indicative list of sensors

This system is real-time because the computer manages the sensor nodes [data-collecting devices] and stores data in real-time, see Figure 2.

TYPICAL APPLICATION OF TECHNIQUES TO YIELD ANALYTICAL RESULTS

Research and experimentation at various institutes in recent years have led to several techniques available for analysing SHM data. They can be combined and applied with convenience to obtain the desired results, providing information about decrements in the performance of bridge structures.

A couple of typical analysis procedures are described below:

1. **Operational Modal Analysis** (OMA), which can be Cepstrum-based, was examined in conjunction with Frequency Response Functions (FRF), Principal Component Analysis (PCA), and Artificial Neural Networks (ANN) by V. V. NGUYEN and Ulrike DACKERMANN et al. [5, 6]

   They used the same technique for frequency response function renewal (FRF). The result of this application was the detection of distress zones. The regenerated FRF data allows for the identification of distressed/damaged features. Excitation and transmission-related effects are included in response measurements. Before relevant transfer functions can be found, their separation is necessary.
   Using the Cepstrum approach, which can handle "frequentially smooth" inputs, the applied technique separates the source from the path.
   Following separation, the transfer path Cepstrum is curve-fitted to obtain the transfer function, from which the desired FRFs are produced.
   They can be made smaller by using Principal Component Analysis (PCA) techniques, which can also serve as an input source for ANN training. An Artificial Intelligence (AI) application to predict the likelihood of distress propagation was produced using ANN training. [8]

2. Meisam GORDAN et al. [5] advised the following for applications utilizing ANN, Frequency Response Functions (FRF), the Imperial Competitive Algorithm (ICA), and CFE: The operational strategies (Inverse Analysis) and diagnosing approaches (ANN/hybrid models) for input data make up two categories of the methodology used in this work.
   Different scenarios were put on the test structure [1:10] after it had been created. As soon as an FRF is created, it is saved in NVGATE. ICATS was used to extract the structural dynamic parameters from the collected vibration data and compute the FRFs using the curve-fitting extraction method. The input for an ANN or a hybrid ANN will be this extracted output [7].

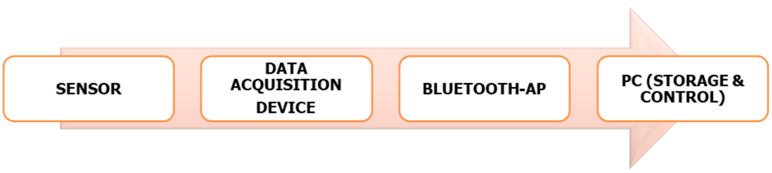

Figure 2: Information flow from a sensor to PC

In the process of Bridge Management, it is critical to identify the cause of distress. When cracks start to appear in the bridge profile, the origin of distress is first recorded.

Most often, crack propagation is the first sign of any visible distress. Integrating Performance with Bridge Management requires several key steps, one of which is connecting the distress symptoms with the cause.

Based on the determination of the source of distress and its correlation with one of the three primary processes - mechanical, physical, or chemical - the Cause matrix in UBMS is evolved [1, 4, 19].

This is primarily done by the Bridge inspection engineer during his long-drawn procedure to record and collate all the information for each element of the bridge from hand touch distance.

This leads to the establishment of a prognosis that defines the cause of distress. Being a prognosis, it is based on the judgment of the inspection engineer and his/her team.

A prognosis based on judgment leads to a scenario wherein such a prognosis must be validated and confirmed by an independent set of procedures and teams. To date, this was done by a non-destructive testing procedure performed at preselected locations by a bridge testing team, to accomplish this. [1, 4, 13]

Our ability to accept the prognosis from direct observation of the bridge's performance under live loads is improved by the option of applying SHM. The performance of a bridge component that exhibits severe distress is recorded.

We can obtain time series information about decrements in performance by the application of short-duration SHM over a period of time. We can construct a reasonable logic to characterize the bridge by connecting this decline in performance with an increase in distress. [13, 18]

The application of SHM allows us to access time series data for elements that exhibit severe distress. Analyzing the SHM time series data, we can determine the progression of distress in those crucial elements on which SHM is deployed.

An algorithm that links the decrements in performance to the increments in distress establishes a procedure to modify the Cause matrix. The integration of SHM within UBMS is based on this algorithm.

The probability matrix for modifying the Cause matrix can typically be as below, see Figure 4.

An increment in distress generates a scenario where we can modify the Cause matrix generated by the prognosis of the bridge inspection engineer/team.

From acceptance of the judgmental prognosis, we have a situation wherein the Cause matrix is modified by actual observation of the performance of the bridge and its elements.

Integration of SHM within the analytics of UBMS steers us away from judgment-based to real-time observation and performance-based decision-making procedure. [4, 8, 9, 13, 18]

With the solution to technical needs taken care of, it is now essential to ensure that a balance between sustainability and financial evaluation is established. Life Cycle Cost Analysis enables UBMS to reach this objective.

Figure 3: Various causes of bridge deterioration

Ratings	9	8	7	6	5	4	3	2	1	0
9	0.29	0.21	0.16	0.34	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.21	0.16	0.13	0.51	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.16	0.13	0.11	0.60	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.13	0.11	0.09	0.67	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.11	0.09	0.08	0.71	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.09	0.08	0.07	0.75	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.07	0.07	0.78
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.07	0.86
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.93
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Figure 4: Probability Matrix

LIFE CYCLE COST ANALYSIS [LCCA] IN ANALYTICS OF UBMS

Detailed financial analysis of a bridge infrastructure is possible with the application of Life Cycle Cost Analysis [LCCA]. Vehicle Operating costs, maintenance costs, and environmental impact costs are considered. Vehicle Operating Costs [VOC] are critical from the user's standpoint because VOC is minimized when bridge infrastructure provides enhanced and improved operational benefits.

The significance of Value of Time [VOT] is critical for both passengers and freight shipments as it is a measure of the saving in time due to the presence of the bridge. Benefits from VOC and VOT savings are direct [tangible] and considered in normal LCCA. [10,11,12,14, 15,16,18]

Generally, this method is adopted to evaluate the Benefit-Cost ratio for any infrastructure including bridges. Apart from these direct costs and benefits, there are not many hidden or indirect (intangible) impacts due to the presence of the bridge.

One classic example of a negative intangible impact is increased gaseous emissions. A few bridges exhibit this negative impact on their surrounding environment, forest, or greenery areas.

The positive impacts arise from the growth in the economic activities within the areas connected by the bridge.

The positive impact appears also due to the increase in connectivity the bridge offers, and the impact on the social life of the populations that use the bridge by offering more opportunities for employment due to ease of travel. [16, 17,18]

The estimation of all such intangible benefits and costs is dynamic and varies over a period. Unless observations and records are available within bridge management to link the dynamics of such changes, it is difficult to estimate and account for such costs and benefits.

Within UBMS, the existence of the Socio-Economic parameter records the changing scenario of the social and economic aspects due to the existence of the bridge. Such records are updated every time an inventory-level inspection is carried out.

Linking the Socio-Economic parameter to evaluate the intangible costs and benefits was overcome by a review of the records and technical review of various previous studies. [1,6,7,8]

Intangible costs and benefits within LCCA calculations and the resultant Internal Rate of Return [IRR] and Benefit-cost ratios are found to be more dynamic and realistic in the UBMS system.

The benefits are enhanced due to the inclusion of intangible benefits for the bridge infrastructure accrued from socio-economic aspects, which represent all benefits arising indirectly from social, economic, and environmental aspects that are considered in the financial calculations.

The bridge structure brings economic benefits from the transport of people and goods across the network. The accessibility, safety, and movement on a bridge are dependent on the population which uses the bridge. It essentially increases the social importance of the bridge. LCCA of such bridge structures must be based on dynamic, robust, and real-time information. UBMS regular updates of all maintenance and rehabilitation activities, real-time increments in distress and its impact on the cause matrix, and resultant dynamic alterations in risk estimation are recorded.

LCCA which is an integral part of UBMS is based on updated records and data in real time. Such a financial evaluation ensures that proper financial due diligence is also included within the bridge management decision-making process.

One such application of LCCA results is illustrated below, showing an enhancement in the IRR evaluation of more than 80%. [18]

IMPORTANCE OF SUSTAINABILITY IN BRIDGE MANAGEMENT

The **objectives of any sustainable bridge** are as follows:

Reducing virgin material use; Optimizing waste stream; Reducing energy use; Reducing emissions to air; Maintaining or improving hydrologic regime characteristics; Maintaining biodiversity; Engaging community values and sense of place; Improving safety; Improving access and mobility; Improving local economy; Increasing lifecycle efficiency; Promoting innovation.

The following **sustainability practices** are related to the planning stage of a bridge:

Addressing scour; Bridge aesthetics; Importance of safety for bridge users; Maintaining or improving access for bridge users including pedestrians and cyclists; Maintaining or improving access for transit; Maintaining or improving aquatic ecosystems; Embracing public participation; Reducing bridge greenhouse gas emissions; Maintaining or improving terrestrial ecosystems; Resilience; Durability; Reducing noise pollution.

The final goals of sustainability are ensured by proper evaluation and implementation as derived from Bridge LCCA.

Reduced cost of construction by increased use of local raw materials, reuse of material, and ensuring recycling of waste generated during the life span of the bridge are a few examples of efficient LCCA management.

Such practices result in less consumption of fuels during the entire life span of the bridge from construction to decommissioning of the bridge.

> *"Sustainable development is a development that meets the needs of the present without compromising the ability of future".*

The sustainability analysis provides direction for improving the sustainability of bridge infrastructure projects and the rationale for undertaking specific actions. [14, 15, 16, 18]

In the bridge engineering community, sustainability means planning, designing, constructing, and managing bridges that maintain a balance between the three pillars of sustainability: social, economic, and environmental considerations.

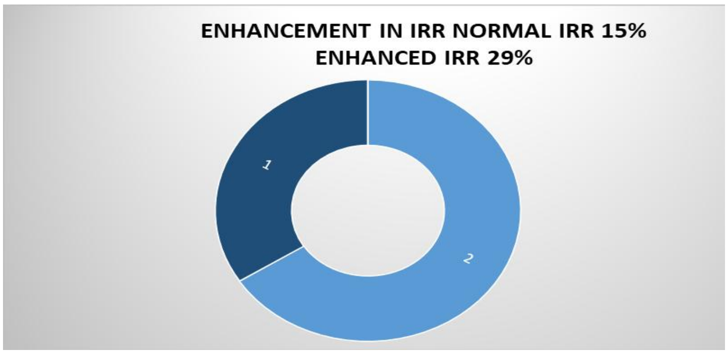

Figure 5: Enhancement in IRR evaluation

While there are many definitions for sustainability, which means supporting the natural, social, and economic systems upon which we depend now and will depend in the future.

A bridge constitutes a large investment of natural, material, financial, and human capital and thus has the potential for significant positive and negative effects on the environment and society throughout its long service life.

If prompt and timely interventions are provided, using a bridge management system it is possible to maintain, strengthen, repair, or rehabilitate a bridge throughout the entire designed service life. This guarantees that bridges will last as designed without needing to be replaced prematurely.

Judicious control of the following factors: cost-effective design application, detour travel time, congestion and traffic jam delay, productivity loss and resultant GDP reduction within the influence area of the bridge results in avoidance of premature collapse needing replacement, increased and stable social benefits, increased network reliability and resultant economic growth and increase in GDP within the influence area of the bridge and finally most important the enhanced safety of the uses [16,18, 20].

LCCA enables the owners to foresee and plan investments in a very cost-effective manner, ensuring sustainability and delivery of the best level of service securely to current and future bridge users in the most cost-effective way. Investments in assets most in need can be prioritized based on the LCCA score. LCCA also permits the cost-optimization necessary to guarantee the bridge's functionality for the duration of its service life.

A risk-based analysis is used to find cost-effective expenditures during the conceptualization, design, construction, and complete operating life of the bridge, ensuring this optimization.

The charts in Figure 6 and Figure 7 show the impact on the financial calculation due to positive and negative socio-economic scenarios.

The main intangible negative impact arises from the negative impact on the environment in the close vicinity of the bridge due to pollution from emissions due to the increased movement of vehicles. Construction of Bridges with high negative impact can be avoided due to LCCA.

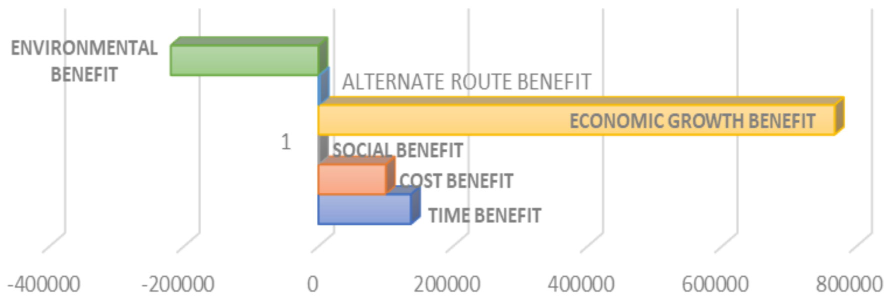

Figure 6: Comparison of Benefits: positive Socio-Economic Scenario

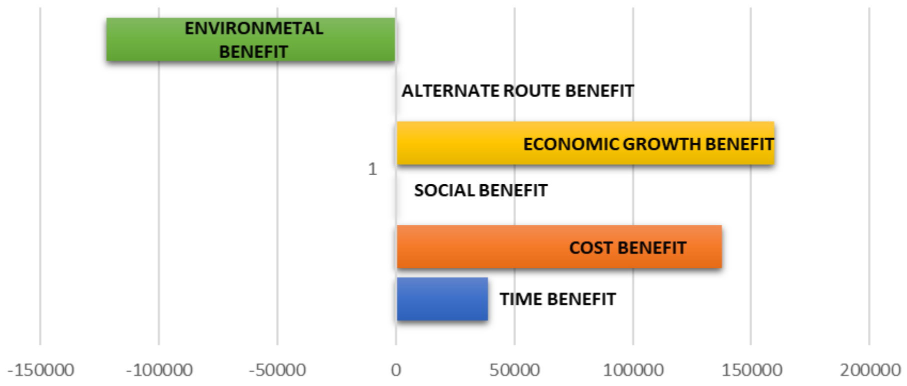

Figure 7: Comparison of Benefits: negative Socio-Economic Scenario

Optimization of fund allocation which is the key fundamental function of any Bridge Management is better governed under the decision-making regime of UBMS. The priority and ranking process in UBMS Analytics defines the priority accorded to a particular bridge from a set of bridges that need rehabilitation intervention.

The impact of LCCA on the ranking process is seen by an actual example of a set of bridges numbered from 1 to 14 for ease of understanding. [18] The ranking when LCCA analytics is not applied, and ranking is based on a conventional process which is determined by W_{sum} is different when the ranking is subjected to analytics using LCCA where the impact of socio-economic parameters and the importance of the type of road are accounted into the ranking process.

The two tables on the following page, Figures 8 and 9, signify the impact of LCCA on the ranking process.

Figure 8 depicts the results when Fund allocation incorporates the finding of LCCA including tangible and intangible costs and benefits resulting in a focus on Sustainability and Economic Growth whereas Figure 9 shows the results without incorporating the LCCA.

CONCLUSION

Since its inception in the United States in the early 1970s, Bridge Management has undergone significant changes. A fully digitized IBMS introduced the digitization process within the Bridge Management system in 2014.

The definition of the Deterioration model is the first step in the Bridge Management process. The risk involved, when remedial interventions are not provided, for a specific bridge is determined using the deterioration model.

Deterioration model aid in choosing the right kind of Cause affecting the structure which in turn help in the definition of the precise corrective action to be adopted for that bridge.

The model enables us to deliver pertinent data for the optimization of fund allocation through the ranking and prioritizing process.

Within the Bridge Management system, this results in deterioration model become extremely important. To characterize the symptom and the process of deterioration, an engineer conducting a bridge inspection must use their professional acumen.

It emphasizes the need to define the deterioration model using a strong, objective and scientific methodology.

Bridge No	Cost of Repairs	Wsum	Rank Bridge	Cumulative Cost	Action suggested
2	10,000,000	120	1	10,000,000.00	Rehab recommended
3	14,000,000	110	2	24,000,000.00	Rehab recommended
4	17,000,000	110	3	41,000,000.00	Rehab recommended
7	10,000,000	110	4	51,000,000.00	Rehab recommended
1	12,000,000	100	5	63,000,000.00	Rehab recommended
5	18,000,000	100	6	81,000,000.00	Rehab recommended
8	12,500,000	100	7	93,500,000.00	Bridge Under Observation
14	16,000,000	100	8	109,500,000.00	Bridge Under Observation
9	16,000,000	90	9	125,500,000.00	Bridge Under Observation
10	17,500,000	90	10	143,000,000.00	Bridge Under Observation
11	14,000,000	90	11	157,000,000.00	Bridge Under Observation
12	18,000,000	90	12	175,000,000.00	Bridge Under Observation
13	11,500,000	90	13	186,500,000.00	Bridge Under Observation
6	13,500,000	70	14	200,000,000.00	Bridge Under Observation

Figure 8: The results when Fund allocation incorporates the finding of LCCA

	Modified ranking and priority					Impact of ABSL, SEBR, and Type of road on Ranking process			
Bridge No	Cost (10M)	Wsum	ABS L	SEB R	BSFR N	Road Type	Ranking/ Priority	Cumulative Cost [Cr]	Action Suggested
2	1.0	120	3.08	3.75	5.5	09	8.81	1.0	Rehab recommended
3	1.4	110	5.71	4.5	5.375	08	7.89	2.40	Rehab recommended
11	1.4	90	3.35	4.25	4.875	08	7.69	3.80	Rehab recommended
12	1.8	90	4.06	4	4.875	08	7.69	5.60	Rehab recommended
6	1.35	70	4.57	4.75	4.625	08	7.52	6.95	Rehab recommended
4	1.7	110	4.47	4.5	5.125	07	7.03	8.65	Under Observation
8	1.25	100	3.04	4.75	4.625	07	6.93	9.90	Under Observation
7	1.0	110	4.03	4.25	5.25	06	6.18	10.90	Under Observation
1	1.2	100	4.22	3.75	5.625	06	6.09	12.10	Under Observation
5	1.8	100	2.43	4.5	4.625	06	6.07	13.90	Under Observation
13	1.15	90	4.13	4	4.625	06	5.99	15.05	Under Observation
14	1.6	100	5.55	4	4.125	04	4.39	16.65	Under Observation
9	1.6	90	7.37	3.75	4.125	04	4.31	18.25	Under Observation
10	1.75	90	4.48	4.5	5.125	03	3.45	20.0	Under Observation

Figure 9: The results without LCCA

Early BMS used the Deterioration model based on symptoms of distress that are recorded. Today, as the depth of knowledge expanded, Bridge Management has switched to an approach, focused on the cause of distress.

This transition from a Symptom-based approach to a Cause-based one took place as a result of EN1504.

This transition was captured and incorporated into UBMS in 2017. Even then the bridge inspection engineer's assessment served as the foundation for the definition of the Cause matrix.

The requirement for a method, independent of judgment, was strongly inspired by the fact that the entire decision-making process was reliant on the judgment of a single person.

The freedom from judgment-based methods was offered by performance monitoring of bridges utilizing SHM.

A barrier in its adaptation stems from the fact that performance needs to be linked to the Cause matrix and resulting Deterioration model to be used in the decision-making process leading to optimization of fund allocation.

The solution was the evolution of an Algorithm linking performance decrements to increments in distress.

Based on SHM raw data, a variety of algorithms are currently available for determining the severity of distress. By employing this definition of degree of distress, its scope, and severity, we can change the Cause matrix.

The modification of the Cause matrix is based on the fact that a decrement in performance implies increments of distress. As a result, the Deterioration model is dynamic, reliable, and impartial.

It is free from the bias resulting from a judgment-based process. The decision-making process is now defined by a real-time model.

Costs are controlled during the whole service life of the bridge.

It makes sure that this takes into account the use of accurate and realistic data for the generation of deterioration models, the inclusion of socio-economic parameters to assess the benefits - Tangible (direct) and Intangible (indirect) that accrue to society as a result of the presence of bridge infrastructure, and the use of the LCCA tool to analyze the costs and benefits during the service life which then is applied to the decision-making process.

Data is regularly being updated under UBMS on a number of socio-economic factors. Application of this data within LCCA ensures the inclusion of a sustainability focus within the decision-making process.

Through this approach, sustainability objectives are also safeguarded. This process ensures that Bridge fulfils present requirements without jeopardizing the ability of future generations to satisfy their own. A sustainable Bridge preserves the harmony between social, economic, and environmental issues.

Using UBMS's Bridge Management Analytics, we ensure that the various economic and sustainable objectives are achieved.

The key strength of UBMS Bridge Management Analytics is that it can be used within any existing Bridge Information System/Bridge Management system.

Minimum requirements of essential data records are either accepted from the existing BMS or the user is allowed to input the data. Analytics of UBMS offers a versatile solution to the existing problems within any Bridge Management.

Further research is not focused on providing a solution that can correlate the distress with the geospatial data which can be provided by BIM or UAV videography.

The goal of future research projects needs to integrate technologies that can provide geospatial information about distress and the ability to create a 3D model of the key components that exhibit severe distress.

Research continues to bring advantages from emerging innovative technologies that encompass our horizon within the folds of Bridge Management.

This ensures the sustained importance of the application of Bridge management in the society we have inherited and shall pass on to the future generation.

Irrespective of who conceptualizes the bridge, who designs the bridge structure, who supervises or who constructs the bridge, bridge structures will continue to be exposed to the vagaries of nature, possible human abuse, and degradation of material from the day they are commissioned.

When the clouds of recession are hovering over the entire world, it is important that Bridge Management delivers more efficient results.

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