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Development of a quality control framework for the highway bridge using KPIs

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Abstract

The development of essential transportation infrastructures such as roads and bridges is critical to the growth of the socioeconomic system. To sustain their service performance throughout the operational stage, it is challenging for the engineers to change their strategy from developing new facilities to maintaining the ageing infrastructure already in place. As a result, this article aims to suggest a quality control framework for managing highway bridges utilizing key performance indicators (KPIs). Case studies are being undertaken for several bridges, most located in European countries. The performance indicators (PIs) and goals (PGs) are formed during this. Then, following the assessment of the vulnerable zone, the derivation KPIs from those PIs are introduced and developed while considering various maintenance situations and time functions. The presentation includes a curated case study focusing on a steel truss bridge. This case study demonstrates the good potential for developing a long-term strategy for managing highway bridges on a lifecycle level.

Keywords: Roadway Bridge; Quality Control; Key Performance Indicators; Spider Diagram; Decision-Making

1. Introduction

There are several national and municipal bridge management systems (Shim et al., 2017, 2019; Dang et al., 2018, 2020). Their architectural frameworks are similar, but their condition assessment techniques differ. These changes can affect maintenance decisions. The highway bridge management process helps identify maintenance needs more consistently. Performance indicators and maintenance strategy planning help establish the procedure. It increases the

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need for quality control (QC) systems to ensure that products and services meet or exceed user and community standards. Road infrastructure asset management and QC go together (Matos et al., 2017, 2020). They are public services, but the state or a private-public partnership can manage them. Both instances require efforts to improve system quality and reduce unexpected expenditures. The standardized approach unites maintenance management formats from diverse networks and nations yet allow them to be integrated with the design because they are already operational. First, quantify performance factors to produce roadway bridge assessment recommendations. These assessment actions have reference periods. Step two is establishing performance standards. Finally, a road bridge QC plan guideline and benchmark implementation examples can be created.

Performance indicators (PI) have been studied in bridge condition assessment ("Fib Model Code for Concrete Structures 2010," 2013; Ugwu & Haupt, 2007). It permits quality control (QC) programs to compare measured PIs to pre-specified performance goals (PG). PIs, especially KPIs, allow to define goals to create QC programs that ensure bridge-quality service. Bridge management techniques can be enhanced by quantifying and assessing bridge performance and quality specifications to ensure an expected performance level, improving asset management of ageing bridges. Management systems commonly employ lifecycle analysis (Yang & Frangopol, 2019). For structural condition evaluation, deterministic performance prediction models explain the future condition through a functional association between structural condition characteristics, such as structural age, and mechanical, chemical, and thermal loading processes (Dhada et al., 2020; Hanley et al., 2016). Such models require precise variable information to implement. Analyzing indicators for assessment frameworks and quantification procedures is crucial.

Thus, performance indicator quantification methodologies must be recommended for assessing roadway bridges. These assessment actions need reference periods. Then set performance standards. That would lead to a quality control plan for roadway bridges, and these plans emphasize advanced deterioration prediction methods. Sustainable roadway bridge management, which evaluates environmental, economic, and social performance indicators throughout the life cycle, is also essential. By quantifying and assessing bridge performance and quality standards to ensure an expected performance level, bridge management methods will be much enhanced, improving asset management of ageing bridges in Europe.

2. Performance indicators and goals

2.1. Performance indicators

Code standards partially cover mechanical and technical qualities and deterioration behaviour, which the indicators capture. Natural ageing, material quality, service life design, sustainable, environmental, economic, and social indicators, and performance profiles are considered. A flexible European performance indicator database meets country-specific needs. Safety, serviceability, availability, prices, and environmental efficiency are measured.

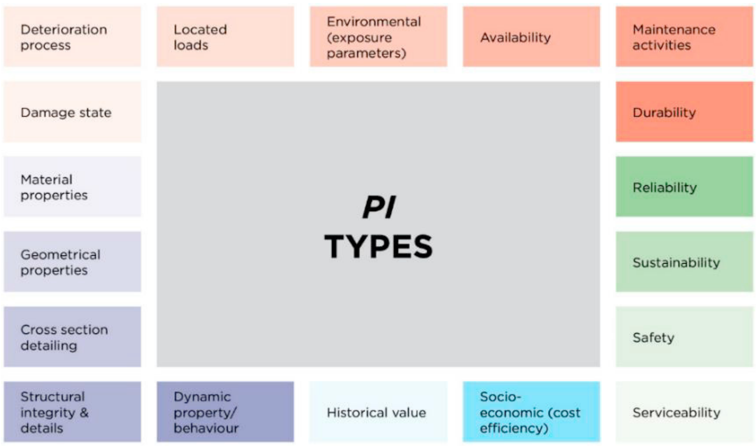


Fig. 1. Possible clusters of research-based performance indicators.

2.2. Performance goals

Figure 2 connects Performance Indicators to Performance Goals at component, system, and network levels. A multi-objective system sets bridge and network performance targets. This study covers five performance aspects: Reliability; Availability; Economy; Environment; Traffic Safety. Multi-criteria decision-making (MCDM) ranks alternatives using inputs, benefit/cost information, and decision-maker/stakeholder opinions. However, performance metrics and goal setting differ across Europe.

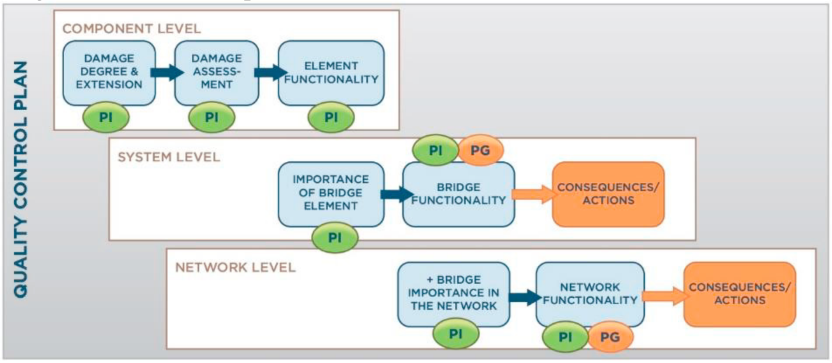


Fig. 2. The assessment procedure from component to the system and network level is based on the PIs and PGs.

3. Quality Control Plan

3.1. Bridge assessment and Quality Control ontology

3.2. Safety and serviceability are apparent KPIs for existing bridges, and durability, stability, affordability, and utility can be added. This paper proposes KPIs (qualitative, between the ordinal scale of 1-5). Safety and serviceability are examined separately, and availability includes serviceability. Spider Net diagrams show performance (Figure 3a). KPI values in the green zone improve bridge performance.

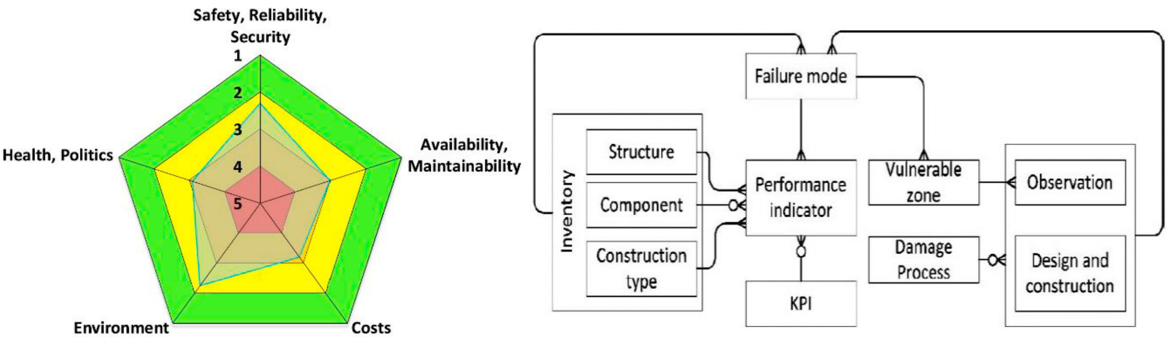


Fig. 3. a) The ‘Spider Diagram’ for bridge assessment; b) The ontology of a Quality Control Framework

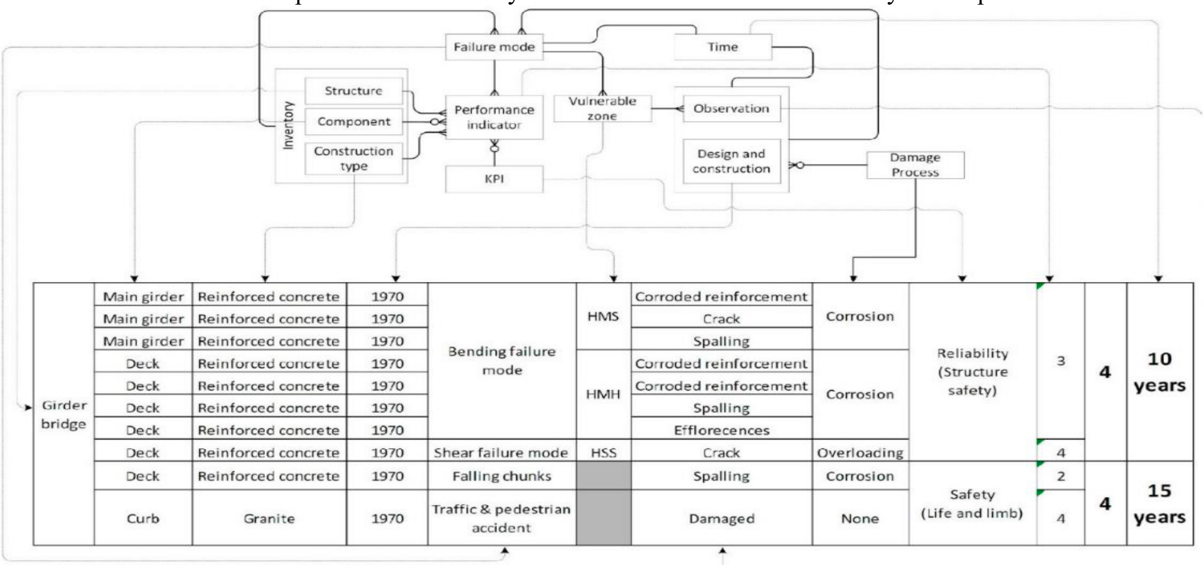
QC will analyze KPIs for alternative maintenance scenarios based on inspection/investigation or prediction to find the best practical one. Ecosystem, economy, and time-based KPIs are helpful. Bridge damage procedures are single or multiple, and therefore knowing about them is essential for performance prediction, preventive maintenance, and rehabilitation. Damage processes are slow and observable (with adequate inspection) or non-observable (handled by an appropriate maintenance strategy). Better damage process information, graded by kind, intensity, extent, location, cause, and impacted material, helps optimize inspection and maintenance procedures.

PIs assess bridge fitness. A crack width > 0.4 mm may indicate reinforcing yield from poor resistance or overloading. Unlike an observation, a PI interprets its effect on bridge performance. Some observations are symptoms; therefore, they don't affect static KPIs (Reliability and Safety). In a dynamic situation, symptoms may immediately affect relevant KPIs (Availability and Economy). This study examines Design & Construction, Observations, Damage Processes, and Symptoms in the QCP framework.

This research uses modern codes' dependability index definition of safety and serviceability, which relates to the target likelihood of a bridge's fitness for purpose during its service life. If existing bridges are unrestricted, reliability evaluation can be economically beneficial. Based on experience and data, a basic reliability assessment can be performed for review. Design documentation can identify relevant failure mechanisms and sensitive zones. Vulnerable zones in bridge structures are where damage most affects safety and serviceability and can be caused by numerous failure modes. Figure 3b shows an Entity Relationship Diagram of the critical entities' broad framework ontology (ERD). The "crowfoot with a circle" represents one-to-zero relationships, whereas the "crowfoot" represents one-to-many relationships.

3.3. Derivation of KPIs from PI

Figure 4 shows a framework ontology-based performance evaluation. The crucial relationship between failure modes/vulnerable zones is organized in a table. BMSs have regarded this information as "engineering judgement" and unconnected to bridge kinds and critical observations. An Owner/Operator decides how urgently to intervene and when the KPI value will hit a preset threshold. Bayesian nets can assess KPI reliability and explain such methods.



Girder bridge	Main girder	Reinforced concrete	1970	Bending failure mode	HMS	Corroded reinforcement	Corrosion	Reliability (Structure safety)	3	4	10 years
	Main girder	Reinforced concrete	1970			Crack					
	Main girder	Reinforced concrete	1970			Spalling					
	Deck	Reinforced concrete	1970		HMH	Corroded reinforcement	Corrosion				
	Deck	Reinforced concrete	1970			Corroded reinforcement					
	Deck	Reinforced concrete	1970			Spalling					
	Deck	Reinforced concrete	1970			Efflorecences					
	Deck	Reinforced concrete	1970	Shear failure mode	HSS	Crack	Overloading		4		
	Deck	Reinforced concrete	1970	Falling chunks		Spalling	Corrosion	Safety (Life and limb)	2	4	15 years
	Curb	Granite	1970	Traffic & pedestrian accident		Damaged	None		4		

Fig. 4. An example of a protocol for performance evaluation derivation of the KPIs from PIs.

3.4. Development of KPIs over time

This research scales all KPIs from 1-5, with 1 being the best and 5 the worst. "Availability," "Environment," and "Economy" KPIs must be scaled from 1-5 in native units. "Availability" is the system's uptime. Each time instant can have a value of 0 or 1. "Availability" can be evaluated by vehicle category-specific journey time, which can be monetized as user expenses. A qualitative "Availability" value can be established based on road importance and alternate routes when models or information are missing. "Economy" follows suit. It normalizes KPIs. As mentioned, a "spider diagram" helps illustrate KPIs. When time is of interest, the time axis can be inserted orthogonally on the diagram plane to each KPI's axis. It creates a "performance tube" (Figure 5).

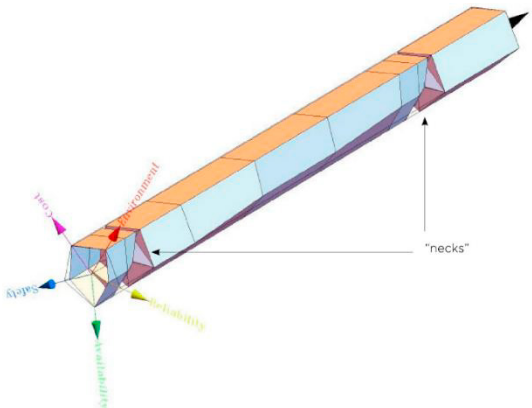


Fig. 5. Generation of a Performance Tube over time for the KPIs.

Serviceability and safety failure types can be analyzed separately on multiple "Reliability" axes. It simplifies maintenance decisions and accounts for failures due to severe deterioration and hazards. "Necks" in the diagram indicate low performance, whereas "complete" pentagon cross-sections indicate good performance. The volume between the "full" pentagon and the "performance tube" could be a performance deficit to be minimized. Using Net Present Value (NPV), monetized KPIs compare future and current events. Non-monetized KPIs divide opinion. Several research on social preference for non-monetized qualities like emotions and values face this difficulty, yet bridge KPIs have some economic influence. Thus, the KPIs "Reliability," "Availability," and "Safety" will be discounted using NPV, like the cash flow and maintenance intervention costs. Today, these KPIs matter more than in one, two, or ten years, and thus, short-term therapies may be costlier but more beneficial. The NPV is divided by the NPV estimated if all KPIs were equal to one across the research period to normalize the KPIs. These long-term KPIs are "average."

3.5. Quality Control framework

Static and dynamic quality control steps are planned (see figure 6). Preparation, inspection, and KPI snapshots make up the first, and the second approach involves determining service life, KPI development, and the best maintenance scenario.

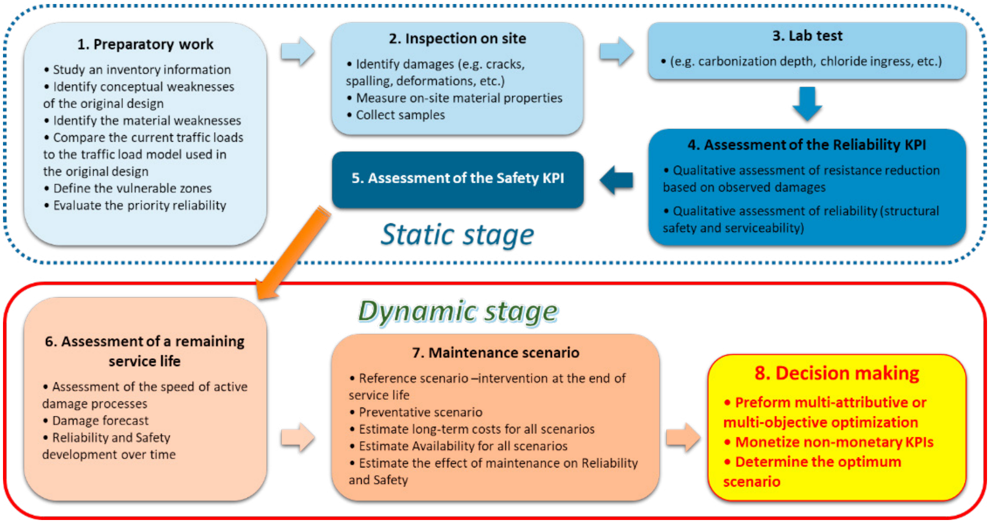


Fig. 6. The steps in the QC Framework.

4. Case study for the steel truss bridge

This research examines a 1956 36m single-span half-through steel truss bridge with a reinforced concrete slab. Road 9779 crosses the Jordan River between Qiryat Shmona and Israel's Golan Heights. The 2012 average daily traffic was 6800, with no heavy vehicle data. Heavy army trucks often pass the bridge. The historical drawing depicts mass-reinforced concrete abutments with four rows of hammered piles penetrating the foundation. Since the pile was built in 1956, it might be steel or wood. The substructure is the substructure of two reinforced (found during investigations) enormous concrete abutments with a deadman block at the back and tension-buried girders.

Fig. 7. Steel truss bridge, Israel.

Structure type	Group	Component	Material	Design & Construction	Failure mode	Location/ Position	Damage /Observation	Damage process	KPI	Performance Indicator component level		Performance value R	Performance value S	Estimated failure time [years]
TB	Structural elements	Main Trusses	Steel	1954	Truss Bending failure mode	Upper chord compression zone	Corroded plates	Corrosion	Reliability (Structure safety)	2.3	4.1	4.1	2.1	40
							Corroded rivet	Corrosion		2.3				40
						Lower chord tension zone	Corroded plates	Corrosion		2.3				40
							Corroded rivet	Corrosion		2.3				40
					Truss Shear failure mode	Diagonals	Corroded plates	Corrosion		2.3				40
							Corroded rivet	Corrosion		2.3				40
							Accidental damage	Impact		2.0				20(?)
					Global buckling of truss upper chord	Connection of truss verticals with deck cross girder	sheared rivet	Fatigue		4.1				15
							Out of plane movement of lower connection plate	Fatigue		4.1				20
		Cross girders	Steel	1954	Bending	High sagging area	Shear connection with deck corroded	Corrosion		2.1	4.1			30
					web plate buckling	Bearing area over main truss	Rivets are partially sheared	Fatigue		4.1				20
					Bending	Along the girder	Corroded rivet	Corrosion		2.1				40
		Deck slab	Reinforced concrete	1954	Bending	HMS/bottom	delamination	Corrosion	Reliability	2.1	2.1			30
				1954	Falling chunks	bottom	Spalling	Corrosion	Safety (Life and limb)	2.1	2.1			30
				1954	Bending	HMH	Efflorescence	Leaching	(Symptom)	(2.1)				
		Bearings	Steel	1954	Bearing Failure	Abutment 1 (west)	Corrosion	Corrosion	Reliability	2.0	4.0			40
		Bearings	Steel	1954	Bearing Failure	Abutment 1 (west)	Bearing restrained no movement due to corrosion and debris	Corrosion	Reliability	4.0				20
		Bearings	Steel	1954	Bearing Failure	Abutment 11 (east)	Loss of rotation ability due to Corrosion	Corrosion	Reliability	3.0				20
		Abutment	Reinforced concrete	1954		Abutment 1 (west)	Spalling and delamination at closing wall	Joint leaking	Reliability	3.0	3.0			20
		Abutment	Reinforced concrete	1954	Bearing Failure	Abutment 1 (west)	closing wall with horizontal crack	Closing of joint	Reliability	3.0				20
		Wing wall	Reinforced concrete	1954		Wing wall	Horizontal cracking		Reliability	2.1	3.3			-
		Wing wall	Reinforced concrete	1954		Wing wall	Spalling	Corrosion	Reliability	3.3				-
		Wing wall	Reinforced concrete	1954		Wing wall	Surface abrasion	Abrasion	(Symptom)	3.3	-			
		Expansion Joint	steel	1954	Closing	EJ 1 (west)	Closing of EJ	Deck movement	Reliability	3.0	3.0			
		Pedestrian Deck slab	Reinforced concrete	1954	HMH	Over transvers supporting truss	Transvers cracks	Not active	Reliability	2.3	2.3			20
		Pedestrian Deck slab	Reinforced concrete	1954	Falling chunks	South Edge	Spalling	Corrosion	Safety (Life and limb)	3.3	3.3	-	3.3	20
	Equipment	Safety barrier	Steel	1954	Falling of the deck	Safety barrier	Broken, missing parts	Impact	Safety (Life and limb)	3.0	3.0			10 (?)
		Pedestrian Handrail	Steel	1954	Falling of the deck	Handrail anchoring	Corrosion of structural steel	Corrosion	Safety (Life and limb)	2.7	2.7			30
		Curb	Reinforced concrete	1954	Falling chunks	Curb side	Spalling, delaminations	Corrosion	Safety (Life and limb)	3.3	3.3			20
		Pavement	Asphalt	Estimated 2005	Sudden disturbance to driver	Expansion joints overlay	Open transvers cracks	Joint reflection cracking	Safety (Life and limb)	3.3	3.3			5

Fig. 8. KPIs for the steel truss bridge, Israel.

Key performance indicators:

KPIs are based on team expertise and Israeli bridge inspection experience (figure 8). Bridge failure modes and signs are estimated. Two life cycle techniques examine the lifetime costs, dependability, availability, and safety of selected truss bridges in the following "100 years". The first method assumes no bridge repairs save pavement ones, and bridge flaws develop until a component or system failure, and only the relevant part or system is fully repaired. A second preventative method considers the initial significant bridge restoration and a later periodical set of timely treatments to prevent defect development and structure degradation. Seismic retrofitting is not required in this circumstance.

Scenario 1 (reference scenario): (figure 9) Only periodic pavement repairs are done on the reference approach. This strategy develops the flaw to bridge failure. Next, assume the following structure faults development and failure times: Pavement collapse in five years owing to expansion joint cracks and potholes will diminish driver safety and raise the risk of accidental impact load impacting the primary truss members. (the reference example requires pavement layer restoration); Accidental damage will collapse the steel safety barrier in 10 years; Due to rivet fatigue, the vertical truss member-cross girder connections are projected to fail in 15-20 years. Based on the faults detected, this problem will progress. It reduces the FEM's safety factor against upper compressed chord global buckling; Based on site climate and present corrosion condition, corrosion will affect bridge components for 30–40 years. Spalling at the bottom of the slab edges and curbs will likely create unsafe circumstances for boat service users travelling below the bridge in 15-20 years. The pedestrian handrail anchoring is corroding and expected to collapse in 30 years.

Scenario 2 (preventative scenario): (figure 10) Preventive maintenance is one of several life cycle techniques. The method assumes the bridge will be fully restored, bringing its reliability index to 'as new'. The intervention will happen two years after design. This massive intervention establishes a 10-year preventive intervention strategy, the 20-year and 40-year periodic intervention expenses. The region bridge maintenance contractor contract process determines costs. Lifecycle: Immediate bridge repair comprises Complete concrete elements repair, concrete curb replacement, joints connection repair including about 400 rivets and plate replacement, overall bridge painting, new expansion joints, bearing rehabilitation, safety barrier replacement with end blocks, pedestrian handrail rehabilitation, pedestrian deck overlay, new waterproofing, and asphalt overlay. Cost includes temporary traffic arrangement. Upper-layer asphalt paving and safety barrier restoration are part of the 10-year intervention based on actual accidents. Temporary traffic arrangements cost. The 20-year intervention involves 10 years + total concrete surface treatments, overall painting system renewal, in-depth NDT of the truss connections before repainting, and EJ rehab/replacement. The cost includes temporary traffic arrangements. The 40-year intervention consists of 20 years + rivet replacement (estimated 500 units), bearing rehabilitation/replacement, deck waterproofing system renewal, and temporary traffic arrangement costs.

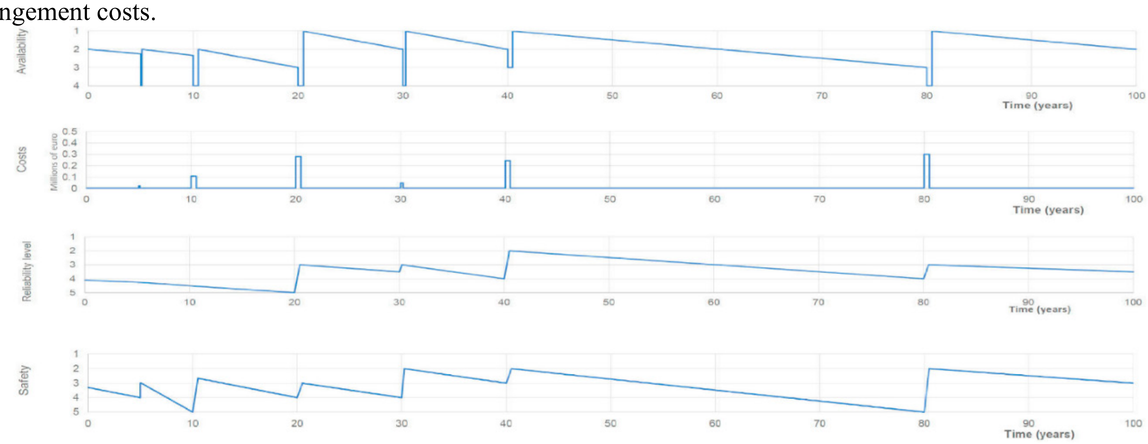


Fig. 9. Evolution of key parameters under reference scenario.

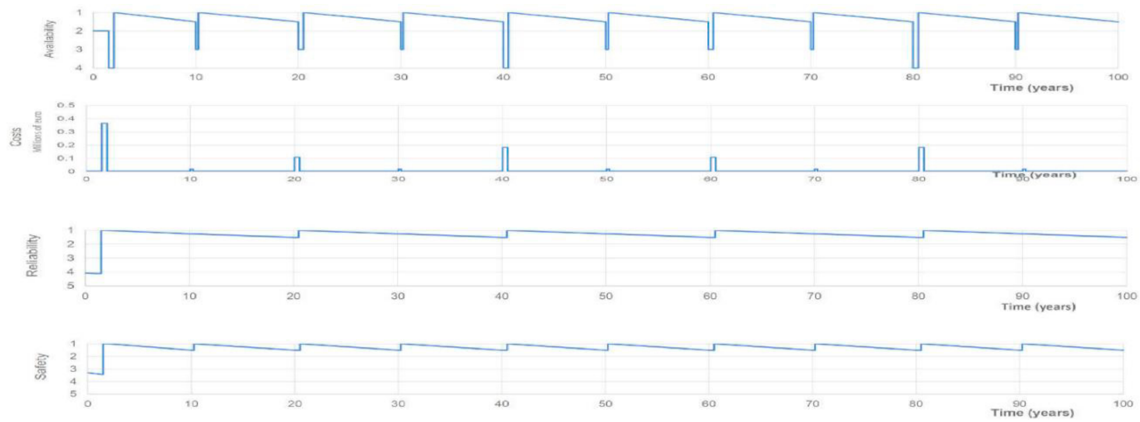


Fig. 10. Evolution of key parameters under the preventative scenario.

Comparison: This "spider diagram" compares the two ways. The analysis suggests a preventative method for this truss bridge. Though more expensive, all other indicators are better. Over time, reliability and safety remain excellent.

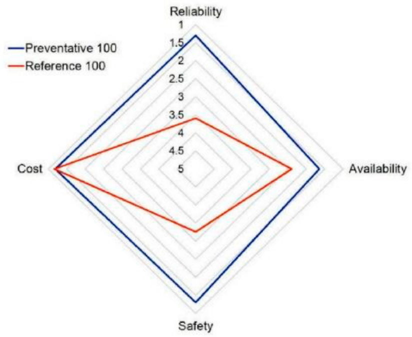


Fig. 11. Spider diagram for the referenced vs preventative approach.

5. Conclusions

This article proposed a KPI-based roadway bridge quality control framework. Performance indicators, vulnerable zone assessment, KPI derivation from PI, and KPI development through time with diverse scenarios are provided for the difficult situations. Finally, a 2-step quality control framework is introduced and proven by a case study, resulting in a strong performance in establishing the roadway bridge's long-term preventative maintenance policy. Conclusions:

- Primary inspection data plan high-quality and timely transportation infrastructure repair. Thus, individual object maintenance costs can be assessed, laying the groundwork for a cost-effective roadway or highway item maintenance strategy. Transferring data and information from design documents and construction to management and operation is crucial to transportation infrastructure management.
- Advanced research, scientific understanding, and mathematical and statistical models can improve roadway infrastructure longevity and degradation prediction. It should gather, analyze, and grade bridge durability data and visual condition assessment should be related to findings. After then, estimates of how long an element stays in a condition can be revised. Then, typical repairs can be connected to bridge condition.
- Civil engineering needs sustainability indicators. Society needs to evaluate products' economic, environmental, and social impacts.

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