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Remedial Modelling of Steel Bridges through Application of Analytical Hierarchy Process (AHP)

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Abstract: The deterioration and failure of steel bridges around the world is of growing concern for asset managers and bridge engineers due to aging, increasing volume of traffic and introduction of heavier vehicles. Hence, a model that considers these heuristics can be employed to validate or challenge the practical engineering decisions. Moreover, in a time of increased litigation and economic unrest, engineers require a means of accountability to support their decisions. Maintenance, Repair and Rehabilitation (MR&R) of deteriorating bridge structures are considered as expensive actions for transportation agencies and the cost of error in decision making may aggravate problems related to infrastructure funding system. The subjective nature of decision making in this field could be replaced by the application of a Decision Support System (DSS) that supports asset managers through balanced consideration of multiple criteria. The main aim of this paper is to present the developed decision support system for asset management of steel bridges within acceptable limits of safety, functionality and sustainability. The Simplified Analytical Hierarchy Process S-AHP is applied as a multi criteria decision making technique. The model can serve as an integrated learning tool for novice engineers, or as an accountability tool for assurance to project stakeholders.

Keywords: steel bridge; deterioration; remediation; asset management; decision support system; health monitoring; Multi Criteria Decision Making (MCDM)

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1. Introduction

Steel bridges are subject to continuous degradation and many of them in existence, which were constructed 50–100 years ago, have exceeded, or are approaching the end of their design life [1]. With many now listed on heritage registers, road authorities have extra incentive to rehabilitate these structures to their former glory. Hence, selecting the most beneficial remediation concept is paramount.

The service life of a bridge can be subdivided into four phases [2]: Phase A—Design, planning and construction; Phase B—Propagation of damage has not yet begun but initiation processes are in progress; Phase C—Deterioration propagation has just started; and Phase D—Extensive damage is occurring. According to the Law of Fives, one dollar spent in Phase A, is equivalent to five dollars spent in Phase B; twenty-five dollars in Phase C; and one hundred twenty-five dollars in Phase D. Implying this rule is the basis for any asset management decision making.

This justifies the importance of employing structured decision support models to assist in improving the bridge network and effective distribution of the allocated budget [3].

Most of the bridge management systems base their decision making process on optimisation of life cycle cost and parameters such as social and environmental impacts are usually ignored. According to

Abu Dabous and Alkass (2008), applying the optimised life cycle methodology may cause difficulties particularly when the available fund is larger or lower than the computed life cycle cost [3].

The benefit to cost (B/C) ratio technique can also be employed at the project level to compare different remediation strategies. This parameter is introduced as the benefit gained by moving from one repair solution to another more expensive option divided by the related extra costs. The benefits include those for both the user and the agency. User benefits are measured in terms of cost reductions or savings to the user as a result of an improvement. Agency benefits are defined based on the present value of future savings because of the expenditures. Over exaggeration of cost as a constraint and subjectivity of benefit evaluation are the negative aspects of this technique.

In mathematical optimisation models, an optimal solution can be reached through the manipulation of the trade-off between the objectives and the constraints. Jiang (1990) constructed an optimisation model using integer-linear programming for the Indiana Department of Transportation (INDOT) [4]. Three key solutions were considered: bridge replacement, deck replacement and deck rehabilitation. Each option is represented a zero-one variable: "0" if the activity is not selected and "1" if it is selected. The model subdivides the decision problem into stages; each year is defined as a stage. The Markov chain technique is used to predict the future bridge condition at each stage, and integer-linear programming is employed to maximise the effectiveness of the network. The only criterion considered in this model was the budget and the fact that only one strategy can be undertaken. As the age of bridge increases, the condition rating gradually decreases [5].

The 1991 the FHWA sponsored a bridge management system (BMS) called "Pontis". This bridge management software was adopted quickly and is one of the primary systems used for bridge management [6]. The current bridge management systems do not provide detailed information for accurately selecting remediation strategies. Hence, many efforts have focused on enhancing the condition rating and maintenance procedures. The development of a decision support system for bridge remediation will complement these efforts.

The research presented in this paper deals with the development of a decision support system for asset management of steel bridges using Multi Criteria Decision Making (MCDM) methods. In infrastructure management, MCDM has emerged as a support to integrate various stakeholder preferences and technical information [7]. These methods are useful ways in optimising decisions under complex environment and can better formulate the problem with respect to reality. They are able to consider qualitative as well as quantitative factors in the decision-making process. However, as each MCDM technique has different properties suited for different problems, there is no simple answer which technique to use for a specific problem. Scoring and weighting systems are critical in multi criteria decision analysis [8]. The proposed model provides an extensive knowledge base for defect identification and selecting appropriate repair methods and is the first decision support system that has been developed for management of steel bridges. Therefore, the proposed system contributes to the efforts aimed at improving the remediation process. To achieve this aim, the following tasks were accomplished:

(1) an extensive literature review;
(2) seeking expert judgment through interviewing asset managers;
(3) developing the model, the knowledge base and the decision tree; and
(4) system validation through a case study.

The quality of the DSS depends on both the quality and extent of its knowledge included. The knowledge base of the developed DSS discussed in this paper was obtained from the literature and also from expert judgement. A questionnaire was sent to bridge asset managers of thirty public and private transportation agencies to collect information about bridge inspection techniques, common remedial strategies and major criteria for decision making.

As illustrated in Figure 1, the proposed model has three main components: System Input including risk assessment and condition rating, the inference element which performs constraints priority ranking and treatment priority setting through a decision analysis tool and finally the system output which is the final remediation plan. A compilation of the most commonly used remediation treatments, following an industry peer review have been used during the development stage of this system. Therefore, the constructed model provides a valuable tool for the verification, or rejection of remediation decisions.

The individual and measurable objectives of this study are to:

- investigate deterioration mechanisms associated with steel bridges;
- explore the constraints that govern the selection of remediation concepts;
- examine the compliance of each concept to the dominant constraints;
- task profile the procedures used by the industry to develop a DSS;
- test and refine the system through a case study to ensure output meets heuristics and industry standards; and
- Systematically recommend a suitable course of action for a given situation.

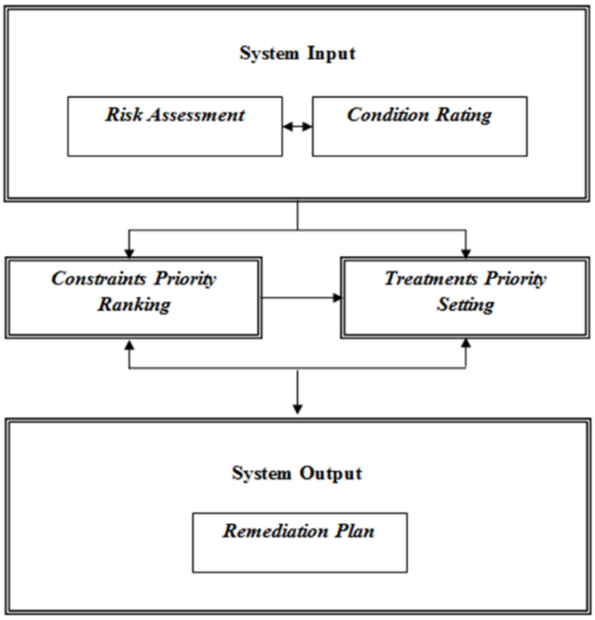

Figure 1. The Proposed Decision Model for Remediation Planning.

2. Deterioration Mechanism

The two most common forms of deterioration in steel bridges are fatigue and corrosion. In some cases, these mechanisms have a combined effect that results in the decline of the structure.

2.1. Fatigue

In steel bridges, fatigue is the most common deterioration mechanism, reported by the American Society of Civil Engineers (ASCE), contributes to approximately 90% of all metallic failures, and is often a limiting factor in the load carrying capacity of steel bridges [9].

The cost involved in maintaining or repairing fatigue related deterioration, can in some instances exceed the initial investment. Similarly, imposed load restrictions due to the presence of fatigue cracks, can result in major disruptions for commuters [10].

Fatigue is a form of fracture failure that results from crack initiation and propagation to final failure of metallic elements subjected to cyclic loading [9]. Failure may occur at stress levels below that of the materials tensile yield stress and is dependent on the application of external loads, geometric features, material properties, and the presence of stress concentrations and/or aggressive environments [9].

Mechanical failure occurs in the presence of stress concentrations that permit fatigue crack propagation under cyclic loading [11]. Common sources of stress concentration include: surface anomalies (roughness, inhomogeneous microstructure, and dents); geometrical variations (sharp edges, notches and threads); and localised forms of corrosion [12].

Crack initiation can be explained with reference to the slip band mechanism at a microscopic level. Upon the application of a cyclic load, displacement of microscopic grains due to sliding crystallographic planes will cause plastic deformation [10]. Dependent on the metallic properties, the exposed slip step may immediately be covered in an oxide layer. Similarly, strain hardening will develop from an increase in the applied load, thus, preventing a reversal of this effect, and introducing microscopic intrusions and extrusions that promote fatigue crack propagation [10].

The transition from crack initiation to propagation refers to growth that is no longer dependent on surface conditions, rather the materials ability to prevent further crack growth [13]. Crack propagation will generally proceed after each cyclic load, in a direction perpendicular to the applied stress. This growth can be represented by benchmarks and striations on the fracture surface that radiate outwards from the point of crack initiation in a concentric pattern [12].

Striations correspond to the growth of fatigue cracks during each cyclic load, and will vary in width dependent on the magnitude of applied stress, whilst benchmarks are indicative of interruptions caused by changes in the applied stress, temperature variations, or the presence of corrosive mechanisms during the propagation stage [10].

Striations (microscopic) and benchmarks (macroscopic) on the fracture surface provide reliable evidence of fatigue failure. The propagation of fatigue cracks will continue until a critical size is reached [10,12].

Fatigue failure will generally occur suddenly and without prior warning in a brittle like manner, once propagation reaches a critical size [9].

2.2. Corrosion

The corrosion of steel is not only limited to steel bridges but extends to all types of steel structures. According to Roberge (2008) the annual cost of corrosion for countries such as the United States, the United Kingdom, Australia, Japan, Kuwait, Germany, Sweden, Finland, China and India is somewhere between one and five per cent of the nation's GNP [14].

The continual shift of anodic and cathodic sites provides the necessary environment for uniform corrosion to prosper. This mechanism works on reducing the thickness and thus, the load carrying capacity of steel members [15]. However, this type of attack is of less concern than more invasive modes such as crevice and pitting corrosion, as it is relatively easy to detect and manage [14].

Galvanic corrosion occurs between dissimilar metals that have varying potential differences when situated in corrosive environments. According to the galvanic series, the metal with the greatest tendency to corrode will become the anode, while the less reactive metal will become the cathode. In the presence of an electrolyte, the anode will corrode as electrons flow from anodic to cathodic regions [10]. The rate of deteriorative loss is dependent on the presence of electrolytes, the potential difference, and the size ratio between cathodic and anodic sites [14].

Crevice corrosion manifests itself in gaps that exist between metals, and metals to non-metals in steel structures, whereby the crevice behaves as the anode and the exterior the cathode. This localised form of attack requires conditions that allow for stagnant pooling of liquids for extended periods of time (e.g., small holes, welds, joints, and around washers and bolts). In some circumstances, crevice corrosion may require over 12 months to initiate, however, deterioration will occur at an ever-increasing rate once the mechanism is developed.

Pitting corrosion is a major cause of steel bridge failure, due to difficulties associated with the detection of pits that are typically covered with corrosive products [14]. The accelerated growth of this deterioration mechanism can be explained by the autocatalytic nature of this process, with surface anomalies generally the origin for deteriorative loss. Temperature is also a limiting factor, as corrosion of some materials will not proceed within a certain temperature range.

3. Condition Rating

Condition assessment is the evaluation of the differences between the as-built and as-is states of the structures. It is an essential step for providing reliable inputs for any bridge management system. In fact, the consistency of decisions to find a remediation strategy or budget allocation is highly dependent upon the accuracy of the diagnosis process and condition assessment. The subject can be a bridge element, a group of similar components within a span, or in all spans, and eventually the entire bridge.

With the aim of being consistent within the common practices the proposed methodology is based on four condition states in which the bridge element condition ranges from 1 to 4 in rising order. The general description of the condition states for reinforced concrete bridge elements is presented in Table 1.

Table 1. Road and Traffic Authority (RTA) condition rating system [16].

Condition State	Description
1	There is no evidence of section loss or damage or cracking.
2	Surface rust or minor pitting has formed or is forming. There is no measurable loss of section. There may be minor deformations that do not affect the integrity of the element. There are no cracks in the steel or welds. All bolts and rivets are in sound condition.
3	Heavy pitting may be present. Some measurable section loss is present locally, but not critical to structural integrity and/or serviceability of the element. There may be some loose or missing bolts or rivets. Defects have been assessed as not sufficient to impact on the final strength and/or serviceability of the element.
4	Section loss is sufficient to warrant analysis to determine the impact on the ultimate strength and/or serviceability of either the element or the bridge. There may be cracks and/or deformations in the steel or welds. There may be numerous failed or missing bolts or rivets. Defects may impact on the strength and/or serviceability of the component.

In this rating system, the bridge is divided into elements generally made of a similar material. The bridge inspector estimates and records the quantities of the bridge element in each condition state independently. The total quantity must be estimated in the correct units for the elements. The measurement units are square meters (deck, pier, and pile), meters (joints and railings) or each (bearing pad, waterway, etc.). Perhaps the most important constraint used to determine the urgency and extent of remediation, is the assigned condition rating given following a bridge inspection. The available concepts for any given situation are dependent on the severity and type of deterioration. For example, the option of no action taken will not be considered for a structure with the highest condition rating following severe corrosion, rather, treatments such as strengthening, rehabilitation, or member replacement will be justified as a plausible course of action [17].

4. Remedial Treatments

Most real-world decisions are drawn from feasible solutions that have been termed as "satisficing" solutions. Several factors influence the decision in any repair and rehabilitation project. Some of these parameters are the availability of funds, severity of the defect, and the effect of the proposed remediation method on the service life of the bridge and also on traffic disruption [6]. In the case of steel bridges, some treatments are exclusive to either fatigue or corrosion remediation while others are suitable for both purposes. Exclusive treatments for corrosion include cleaning and painting, thermal metallic spraying and cathodic protection. For fatigue, crack repair treatments, removal of the crack tip by drilling and member strengthening, can be used. Bolting or welding splice plates and member replacement are suitable for the remediation of both deterioration mechanisms. The following are the main treatment options.

4.1. Crack Repair

Fatigue cracks that originate from sources of stress concentration, geometric variations, or from localised corrosive deterioration are often encountered by bridge inspectors and engineers. If these cracks are not repaired in a timely manner, a severe reduction in load carrying capacity may be experienced [18].

Crack-stop holes are extensively used for emergency repair, whilst, a more permanent solution is sought after and engaged [19]. This involves a hole of specific diameter drilled at the tip of the formed crack, thus, relieving the stress concentration. The crack-stop hole may then be sealed with epoxy resins, or protective coatings to prevent the ingress of moisture. The installation of a tensioned bolt, or cold expansion around the perimeter of the hole, may also be exercised for improved strength characteristics. It must be mentioned, that the above methods will not guarantee further crack propagation, thus continual monitoring of the structure is a necessity.

Alternatively, epoxy based resins can be used to prevent the ingress of air and moisture in minor fatigue cracks. For more significant cracking found in compression members, field welding is generally undertaken, while, for tension members the perceived safety risk of welding often leads authorities to alternate methods, such as member replacement.

In addition, shot peening and Ultrasonic Impact Treatment is an effective technique used to extend the fatigue life, improve reliability, and reduce subsequent maintenance costs for steel structures [19,20]. These properties are achieved by propelling small hard particles at high velocities onto metallic surfaces, thus inducing compressive stresses on the surface [10].

4.2. Cleaning

Cleaning of steel structures is primarily undertaken to remove debris or other contaminants prior to the application of a new protective system, and should be conducted in accordance with standards for preparation and pre-treatment of surfaces. Hand-tool, power-tool, and abrasive blast cleaning methods are most commonly used within industry.

4.3. Protective Coating

Protective coatings applied following adequate preparation, not only provide a physical barrier between the environment and structure, but may also satisfy aesthetic needs [21]. The compatibility of existing and proposed costing systems requires deliberation prior to final selection. The two most widely accepted protective systems include: paint and metallic coatings.

4.4. Cathodic Protection

Cathodic protection is based on the notion that the cathode in a galvanic cell will not corrode. The wide spread application of cathodic protection has been seen around the world for use on steel bridges [10]. An induced electrical current or less noble metal may be used as the sacrificial anode for this process [22].

Sacrificial anodes provide an inexpensive and effective means of cathodic protection, whereby less noble metals supply additional electrons to the structure, to prevent the formation of corrosive mechanisms. Routine monitoring of the structure will ensure continued protection, as an electrochemical path free from obstructions, such as air pockets or insulators is required.

Impressed current supplied via an external power source is another effective defence mechanism that exploits the idea of cathodic protection. Specially mounted anodes linked to the positive terminal are connected to the structure through the negative terminal [14].

4.5. Strengthening

Strengthening is often adopted as a preferred remedial measure for deteriorative loss or fatigue cracking, as opposed to the more expensive and arduous task of member replacement. Recent developments in this field have led road authorities to consider alternatives such as FRP wrapping, other than conventional steel plate strengthening [23].

Bolting or welding additional strengthening or splice plates to increase the cross sectional area of deteriorated steel components, has been successfully implemented by many road authorities around the world. However, induced stress concentrations and distortions introduced during this process, may contribute to reduced structural performance. Inadequate friction between bolted members can often impede the transfer of loads through these strengthening plates. Likewise, welding items to deteriorated members may severely diminish structural integrity. Hence, thorough evaluation of the structure is required prior to the selection of a given course of action, to ensure compliance is achieved.

Problems introduced during the mechanical attachment of steel strengthening plates, such as those previously mentioned, can often limit the structures service life. Thus, the use of emerging technologies, especially from the fibre reinforced polymer industry, has resulted in favourable outcomes for road authorities. In particular the use of carbon fibre reinforced polymer strips, have provided such benefits as: reduced weight; non-corrosive characteristics; high stiffness and strength-to-weight ratios; ease of installation to problem areas; improved fatigue properties; and lower maintenance costs. Hence, the use of FRP for strengthening purposes is gaining momentum within industry. However, further research into the long-term capabilities of this technology is required before absolute confidence can be obtained [23].

4.6. Member Replacement

In the event that deterioration is beyond economically feasible or beneficial repair, member replacement can be considered. Examination of the bridge will determine the parameters of rehabilitation. With temporary supports, load restrictions, or diverting traffic, typical courses of action exercised by road authorities during the remediation process. Hence, significant cost and disruptions on the road network come about from member replacement [17].

Table 2 shows the major deterioration and defects, causes, common locations, detection methods and common strategies for remediation of steel bridges. The available concepts flowchart, as seen in Figure 2, illustrates the treatments considered for a given situation, after non applicable concepts have been "pruned".

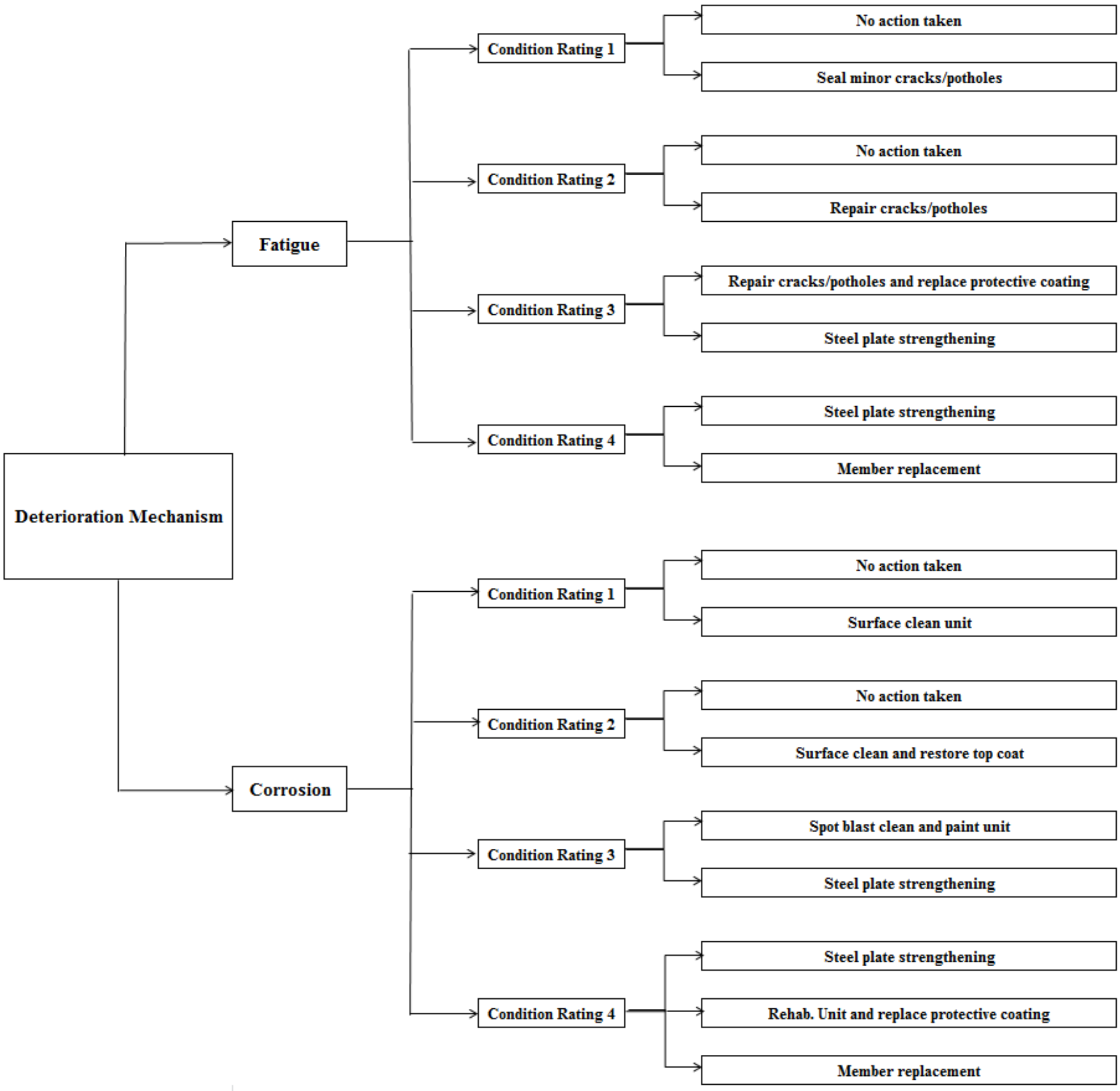

Figure 2. Available Concepts for Each Given Deterioration Scenario.

Table 2. Major Defects, Causes, Common Locations, Detection Methods and Remediation Strategies for Steel Bridges.

Deterioration	Sub-Categories	Causes	Common Locations/Detection	Remediation Strategies
Corrosion	Surface corrosion	Surface corrosion caused by either direct chemical or electrochemical attack with the production rust of the surface of a metal.	Common Locations: >Corners. >Riveted joints. >Deck joints. Detection: >Visual Inspection. >Acoustic emission.	Cleaning and Painting: >Brushing. >Spot repairs concentrate on the small areas of corroded steel. >Spot repairs plus over coating. >Full coat removal and repainting of the bridge. >Abrasive shot blasting. >Flame cleaning. >Acid pickling. Protective Coating and Cathodic Protection: >Primer and Painting (Zinc Rich vs. Aluminium Rich), >Thermal spray metalizing, >hot dip galvanising, >Chlorinated rubber coating. >Epoxy. Reinforcement: >Steel plate reinforcement. >CRFP reinforcement. >Member Replacement.
	Pitting corrosion	Pitting corrosion is where small holes and pits form from extremely localised corrosion. The pitting corrosion can be formed between metal and metal or non-metal materials.	Common Locations: >Horizontal surfaces. >Corners. >Any places of water ponding. >Locations of untreated corrosion where a layer of rust has been formed. Detection: >Visual Inspection. >Acoustic emission.	
	Crevice corrosion	The build-up of debris and corrosive substances in small gaps or crevices in the structure creating a stagnant environment underneath, make it difficult to spot the development of crevice corrosion. The crevice might be formed by a bolted joint or rivet even non-metallic materials.	Common Location: >Bolted Reinforcement plates. >Riveted reinforcement plates. >Gusset plates. >Splice plates. Detection: >Visual Inspection.	
	Galvanic corrosion	Occurs due to contact between two different metals which are exposed to some form of corrosive instigator such as rainwater and seawater. In this process, the two metals which have different reactive potential are in contact with a conducting and corrosive liquid.	Common Location: >Welded joints. >Bolted Joints. >Riveted Joints. Detection: >Visual Inspection.	

Table 2. *Cont.*

Deterioration	Sub-Categories	Causes	Common Locations/Detection	Remediation Strategies
Cracking	Stress corrosion cracking	Stress corrosion cracking is the cracking induced from the combined influence of tensile stress and a corrosive environment.	Common Location: >Cover plates and gussets. >Web connection plates and eye-bars and pin plates. Detection: >Dye penetrant method.	Surface Cleaning and Corrosion protection: >Abrasive blast cleaning + protective coating. >Primer and painting. >Epoxy. >Chlorinated rubber coating. >Member Replacement.
	Cold cracking (hydrogen cracking or hydrogen embrittlement)	Cold cracking are induced by the brittle microstructure and the presence of the hydrogen as well as the accumulations of stress level.	Common Location: >Web connection plates, cover plates and gussets. Detection: >Dye penetrant and Radiography methods.	>Hydrogen "Bake-out" (Heat Treatment).>Member Replacement and the using of peening techniques.
	Fatigue Cracking	Fatigue cracking can be induced where there is a defect in welds during fabrication, and if there are fluctuating stress occurring internally or there is inappropriate structural component where has low fatigue strength.	Common Location: >Rivet Holes. >Bolt Holes. >Welds. >Bracings under wind or traffic loads. Detection: >Piezoelectric sensor. >Acoustic Emission.	>Bridge down-grade. >Drill hole at tip of crack. > Crack Stitching. >Mechanical Peening. >Ultrasonic Peening. >Plate Reinforcement. >CFRP Reinforcement. >Member Replacement.

5. Risk Assessment and Criteria Selection

The decision making process involves a case-by-case evaluation, to identify the potential risks associated with any course of action. Bridge asset managers have various criteria that must be coped with when endeavouring to propose the best possible action for bridges. The main idea of using criteria is to evaluate the performance of alternatives in relation to the goals of the decision maker based on a numeric scale. According to Lemass and Carmichael (2008), as a result of incomplete information, uncertainty, misinformation and the changing priorities of decision makers, the list of technical constraints should be bounded by the inclusion of subjective criteria such as safety and reliability [24].

These important constraints and their interrelationships were identified through the expert judgement obtained from the questionnaire. Table 3 shows the identified risks and subsequent constraints for bridge remediation. This list is by no means inclusive, with other project specific criteria identified during the risk evaluation process.

Table 3. Major Risks and Client Constraints for Bridge Remediation.

Criteria	Risks	Client Constraint
Safety	Potential injury/fatality Damage to property	Minimal damage/Maximum safety of the public
Serviceability	Low level of service Difficult to access the element Insufficient level of expertise Closure of a strategic/regional route	Maximum service life Easy access to element/site Maximum availability of skilled labour Minimal traffic disruption
Sustainability	Excessive remediation cost Excessive work implications Environmental damage	Minimal cost Minimal work implications Minimal environmental damage
Legal/Political	Major changes in standards	Minimum vulnerability to legal/political pressures

6. Decision Analysis Tool

Multi Criteria Decision Making (MCDM) tools are used in order to deal with various problems that engage criteria and to attain greater transparency and accuracy of the decision making process [2]. MCDMs go deeper along a holistic approach, aggregating all the data including that of a subjective nature. Almost all the MCDM approaches share some common mathematical components: values for decision alternatives are allocated for each criterion, and then multiplied by associated weights to produce a total score [7].

Various decision making tools have been investigated. Simple Multi Attribute Rating Technique (SMART) and Analytical Hierarchy Process (AHP) have been identified as the most applicable techniques.

Analytical Hierarchy Process (AHP) is a multi-attribute decision making method that belongs to a broader category of tools known as "additive weighting methods". The AHP was proposed by Saaty (1991) and employs an objective function to aggregate the different aspects of a problem where the main goal is to choose the option that has the highest value of the objective function. AHP is grouped as compensatory methods, in which constraints with low scores are compensated by higher scores on other factors, but in contrast to the utilitarian techniques, the AHP uses pair wise comparisons of criteria where all individual criteria are paired with all other criteria and at the end results accumulated into a matrix [25]. The advantages of the AHP method are that it offers a systematic approach through a hierarchy and it has objectivity and consistency. On the other hand, the main limitations are that calculation of a pair-wise comparison matrix for each factor is a complex task and as the number of alternatives and/or criteria increases, the number of calculations for comparison matrix rises considerably. Moreover, if a new option/alternative is added, all the calculations have to be restarted [26].

The process of AHP includes three phases: decomposition, comparative judgments, and synthesis of priority. Through the AHP method, decision problems are decomposed into a hierarchy, and both qualitative and quantitative data can be used to derive ratio scales between the decision elements at each hierarchical level by means of pairwise comparisons. The top level of hierarchy represents overall goals and the lower levels correspond to criteria, sub-criteria, and alternatives. With comparative judgments, decision makers are requested to set up a matrix at each hierarchy by comparing pairs of criteria or sub-criteria. A scale of values ranging from 1 (indifference) to 9 (extreme preference) is employed to express the preferences. Finally, in the synthesis of priority stage, each comparison matrix is then solved by an eigenvector technique for determining the weight of criteria and alternative performance.

The comparisons are often documented in a comparative matrix, which must be both transitive such that if, $i > j$ and $j > k$ then $i > k$ where i, j, and k are alternatives; for all $j > k > i$ and reciprocal, $a_{ij} = 1/a_{ji}$. Priorities are then estimated from the AHP matrix by normalising each column of the matrix, to derive the normalised primary eigenvector by $\mathbf{A}\cdot\mathbf{W} = \lambda_{max}\cdot\mathbf{W}$; where **A** is the comparison matrix; **W** is the principal Eigen vector and λ_{max} is the maximal Eigen value of matrix **A** [26,27].

Through the AHP process, inconsistency of the comparisons can be estimated via consistency index (CI) which is used to find out whether decisions break the rule of transitivity, and by how much. A threshold value of 0.10 is considered satisfactory, but if it is more than that then the *CI* is estimated by using the consistency ratio $CR = CI/RI$ where *RI* is the ratio index. *CI* is further defined as $CI = ((\lambda_{max} - n))/((n - 1))$; where λ_{max} as above; n is the dimension [27]. The average consistencies of ration index RI from random analysis are shown in Table 4.

Table 4. Random Inconsistency Index [28].

N	*RI*
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

The key advantages of the AHP method are that it presents a systematic approach and it has reliability and objectivity and for calculating weighting factors for criteria [29]. It can also provide a well-tested technique which allows analysts to include multiple, non-monetary attributes of decision alternatives into their decision making.

Simple Multi Attribute Rating Technique (SMART) is independent of the decision alternatives. While the incorporation of value functions makes the decision modelling process somewhat complicated, the advantage of this method is that the ratings of choices are not relative, therefore shifting the number of alternatives will not in itself change the decision scores of the original options [30]. If new items are necessary to be added to the model after its initial construction, and the alternatives are acquiescent to a direct rating method, then SMART can be a suitable option

A rational balance has to be made between the simplicity of SMART and complexity of AHP. In this research identification of the appropriate criteria and weighting them have been of great significance. The eigenvector approach of AHP is a suitable method to provide accurate and reliable judgements and its advantages justify its complexity. The proposed method is a combination of these two techniques, introduced as Simplified Analytical Hierarchy Process (S-AHP) which will be further explained in the following section.

Strategy Selection Using S-AHP

Through the S-AHP, the problem is broken down into a hierarchy, including three major levels: goal, criteria (objectives) and alternatives. Sometimes the decision criteria are required to be broken down into more specific sub-criteria in another level of hierarchy.

S-AHP deals with identifying the main goal and proceeding downward until the measure of value is included. Figure 3 shows a four-level hierarchy structure considering the general aspects of the problem. The overall goal of the ranking is Bridge Remediation. The second level holds the main objectives (criteria) to achieve the goal. The third level contains the sub criteria to be employed for assessing the objectives. The final level includes the remediation alternatives. Each item has a weight indicating its importance and reflecting the organisational policy. These weights are defined and allocated by the decision makers using the pair wise comparison approach embedded in the AHP system and will vary for different problems with different decision makers [31]. The AHP has the key benefit of allowing the users to conduct a consistency check for the developed judgment regarding to its relative importance among the decision making items. Therefore, the decision maker(s) can modify their evaluations to supply more informed judgments and to improve the consistency. The allocated weights in Figure 3 are based on an expert judgment for a generic Bridge Management System (BMS).

The procedure can provide flexibility in selecting the criteria to be used and even decreasing or increasing the numbers of levels (associated with the criteria) in the hierarchy.

The overall value of each alternative for a four level hierarchy (as shown in Figure 3) X_j is expressed as follows:

$$X_j = \sum_{i=1}^{n} W_k W_{ki} a_{ij} \tag{1}$$

- $j = 1, \ldots, m$
- W_k is the overall weight of criterion k
- W_{ki} is the overall weight of the ith sub-criterion in the category of criterion k
- a_{ij} is the ranking of jth alternative in respect to the ith sub criterion and kth criterion.

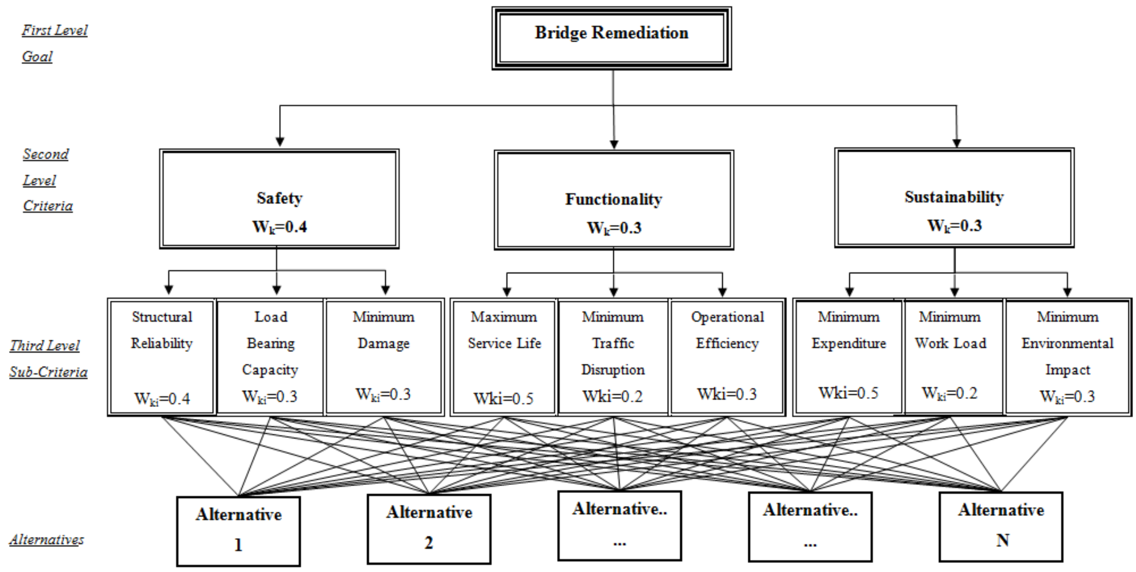

Figure 3. Typical Hierarchy Structure for Bridge Remediation [17].

Figure 4 presents a flow chart of the proposed ranking procedure for strategy selection, which can be applied for each bridge that requires intervention.

After criteria selection, the eigenvector approach of AHP will be used in order to define the vector of constraints' priorities. Finally, the SMART technique will be applied to rank the remedial options.

Generally, because of budget limitation, bridge asset managers have to define the level of satisfaction for the different elements, considering the structural significance and material vulnerability of those components. For example, a bridge manager may decide to leave a barrier with the ESCI of 3 in service for a long period of time contenting to some general routine maintenance. The system does not have any default for that and the system user (decision maker) should assign the target values for the acceptable threshold of element condition. The most applicable alternatives are primarily proposed by the inspector(s) mainly based on technical considerations and further refined by the bridge maintenance planner.

Figure 4 shows the flowchart of the proposed method for strategy selection and remediation planning.

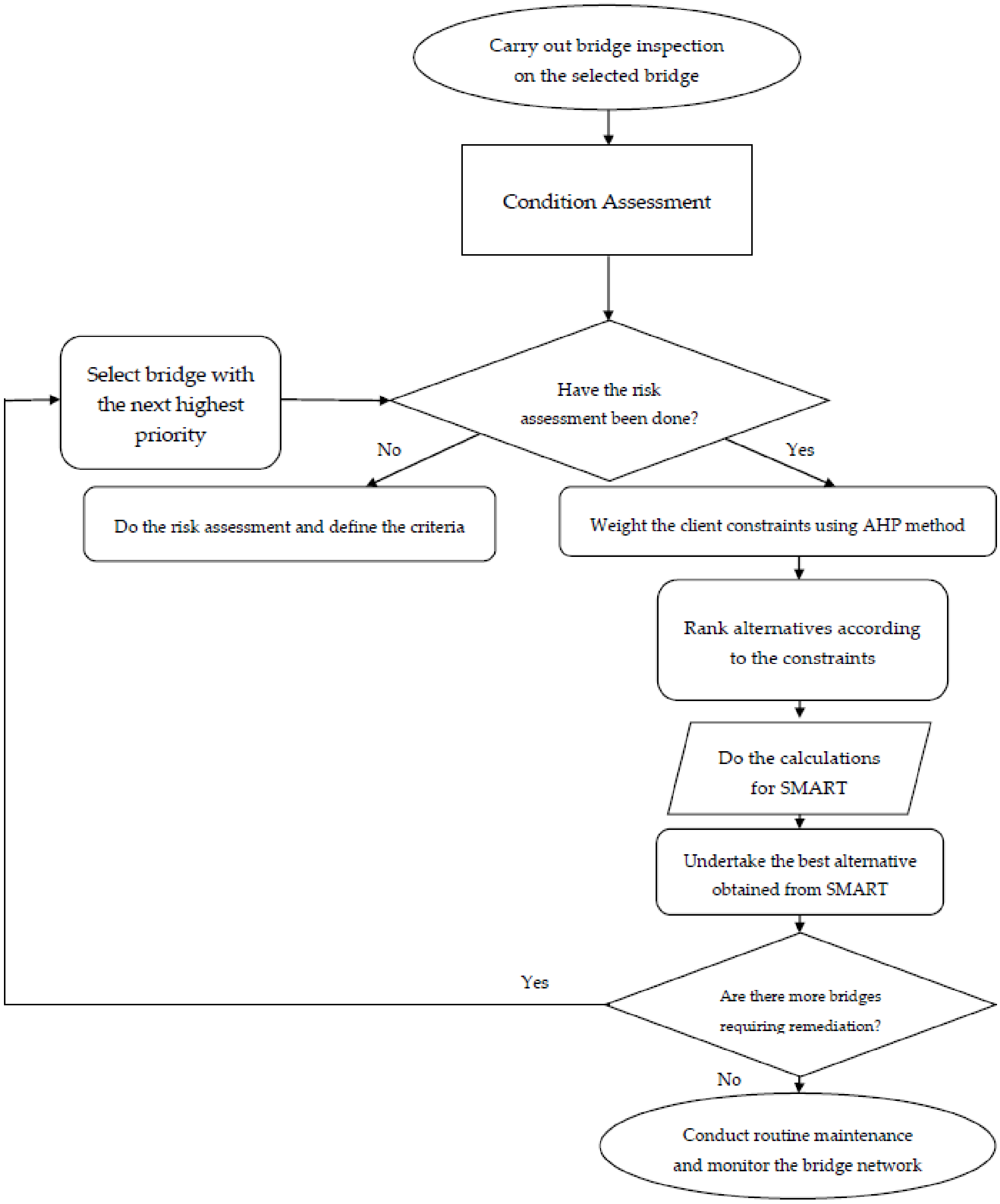

Figure 4. Flow Chart of the Proposed Method for Strategy Selection at Project Level.

7. Model Validation through a Case Study

To ascertain the relevance of the proposed system in practical situations, a case study (courtesy of RMS) was used for testing. The chosen scenario involved severe pitting corrosion on the underside of the top chords of all steel truss spans, including the lift-span truss, on the Bateman's Bay Bridge as depicted in Figure 4. This iconic landmark, in service since 1956, plays a pivotal role for transportation on the South Coast of NSW, thus, efficient rehabilitation of the structure is paramount.

After visual inspection of the bridge by the author, it was determined that the bridge has considerable corrosion on the surface of the steel, making up approximately 15% of the total area of the structure. The surface corrosion on the structure is therefore classed as severe. Other defects noted on the structure include pitting rust on the underside of the members on the truss span, breaking down of paint on the top and western edges on the plate girder spans. There was also some crevice corrosion occurring around joints.

As a conclusion, deterioration mechanism and condition rating were specified, as corrosion and 3, respectively. For these constraints, four possible courses of action have been nominated. These included: splice plates; steel plate strengthening; fibre reinforced polymer strengthening; and partial member replacement. The dominant criteria proposed by the asset manager were Safety, Service life, Remediation Cost, Traffic Disruption, Environmental Impact and Heritage Significance/Aesthetic Appeal. Figure 5 illustrates the three level hierarchy structure constructed for remediation planning of the Bateman's Bay Bridge.

Figure 5. Bateman's Bay Bridge (Photo: Taken by the Author).

The experts were then requested to compare the major criteria in pairs with respect to the overall goal. The AHP method has been applied to determine the vector of priority (VOP) for the introduced objectives based on the experts' judgments. The AHP matrix and the VOP (eigenvector of the AHP matrix) are presented in Figure 6 and Equation (2), respectively.

$$\text{VOP} = \begin{bmatrix} 0.1376 \\ 0.4581 \\ 0.2627 \\ 0.0453 \\ 0.0663 \\ 0.0299 \end{bmatrix} = \begin{bmatrix} \text{Service Life} \\ \text{Safety} \\ \text{Cost} \\ \text{Environment} \\ \text{Traffic Disruption} \\ \text{Heritage/Aesthetic} \end{bmatrix} \quad (2)$$

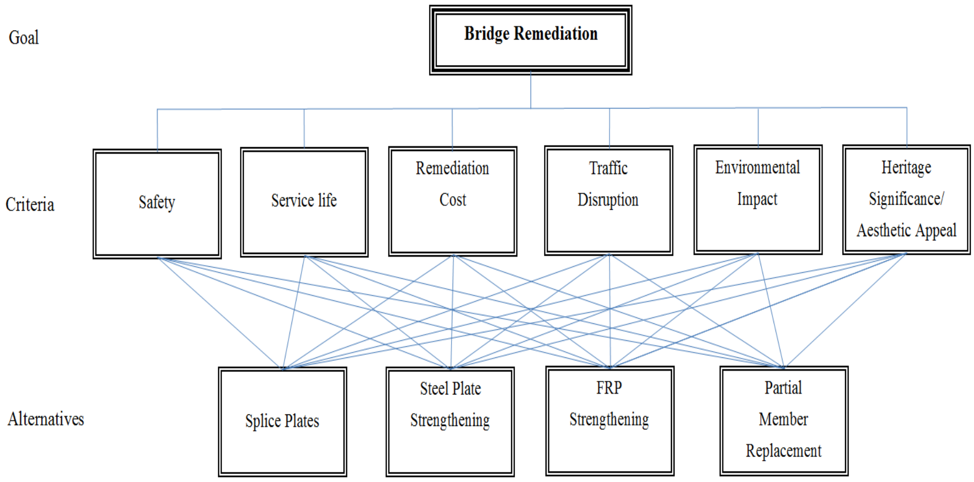

Figure 6. Three Level Hierarchy Structure for Remediation of Bateman's Bay Bridge.

Figures 7 and 8 illustrate the application of AHP and pairwise comparison of the identified criteria in the developed system.

	Service Life	Safety	Cost	Environmental Impact	Traffic Disruption	Heritage Significance
Service Life	1	1/5	1/3	5	3	5
Safety	5	1	3	9	7	9
Cost	3	1/3	1	7	5	9
Environmental Impact	1/5	1/9	1/7	1	1/3	3
Traffic Disruption	1/3	1/7	1/5	3	1	2
Heritage Significance	1/5	1/9	1/9	1/3	1/2	1

Figure 7. AHP Matrix for Criteria Weighting.

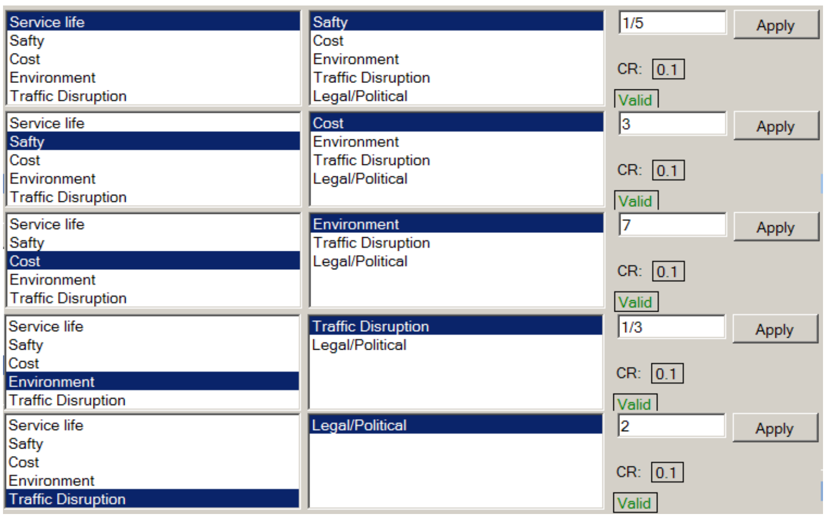

Figure 8. Pairwise Comparison of the Major Criteria in the Developed DSS.

Since the decision makers may be unable to provide consistent pairwise comparisons, it is demanded that the comparison matrix should have an adequate level of consistency, which can be checked by using the following consistency ratio (*CR*):

$$CR = \frac{(\lambda\text{max} - n)/(n-1)}{RI} \tag{3}$$

where,

$$\lambda_{max} = 9.73(0.1376) + 1.9(0.4581) + 4.79(0.2627) + 25.33(0.0453) + 16.83(0.0663) + 29(0.0299) = 6.59$$

In order to calculate λ_{max}, the values in front of brackets are the summations in AHP matrix in Figure 7, and the quantities inside the brackets are the corresponding VOPs.

Random inconsistency index (*RI*) is extracted from Table 4 provided by Saaty (2004). The Consistency Ration (CR) has been estimated based on Equation (2). Since the value of CR is less than 1 (see Equation (4)), the accomplished judgement is consistent.

$$CR = \frac{(\lambda\text{max} - n)/(n-1)}{RI} = 0.095 < 0.1 \tag{4}$$

As shown in Table 5, four different alternatives have been identified for rehabilitation of the affected area: "Splice Plates"; "Steel Plate Strengthening"; "FRP Strengthening"; and "Partial Member Replacement". All the above mentioned options have been ranked against the given criteria (using SMART method) and their overall scores have been estimated using Equation (1). "Partial Member Replacement" obtained the highest score in this decision analysis. The system has performed well against past decisions undertaken by the RMS in 2009.

To rehabilitate this historical bridge and to avoid potential litigation, RMS performed member replacement on the deteriorated sections. The decision was found to be in union with the recommended course of action provided by the system.

Table 5. Global Priorities of Different Major Strategies.

Criteria \ Alternative	Weights/%	Splice Plates	Steel Plate Strengthening	FRP Strengthening	Partial Member Replacement
Service Life	13.76	3	4	4	5
Safety	45.81	4	4	4	5
Cost	26.27	3	2	3	2
Environmental Impact	4.53	3	3	4	3
Traffic Disruption	6.63	2	2	3	1
Aesthetic Appeal	2.99	2	2	3	4
Overall Score	100	336.16	204.37	364.07	382.57

8. Conclusions

The digital revolution and artificial intelligence have opened the door for smarter infrastructure. Nowadays, scientists and practitioners have the technology to understand how a tunnel, a building, a bridge, or a railway line is performing during its service life. This will lead to improved asset management, as decision makers will know how to prioritise the assets and when, and how, to manage it more competently. Application of decision support models for management of civil infrastructure also enables more economic design, reduced costs and greater efficiencies, both in the cost of construction and in the subsequent asset management costs, delivering benefits to multiple stakeholders [32].

Corrosion and fatigue can have a detrimental effect on the serviceability and structural lifespan of a steel bridge. Corrosion caused by the oxidation of the iron can attack the structure and eventually shrink the cross-sectional area of the member. It can also freeze joints which are assumed to be free to move, such as pins, bearings and hangers. Fatigue cracks initiating from high stress regions can propagate through the members in the structure, essentially causing the member to loose cross-sectional area. Both of these reduce the load carrying capacity of the bridge. This research has proposed a decision system for the remediation of steel bridges based on multi-criteria analysis. The mechanism of deterioration on steel bridges were investigated and identified and the remediation treatments used for these deterioration mechanisms have been analysed. The decision system based on the Simplified Analytical Hierarchy Process (S-AHP) has been proposed as the main model for strategy selection. In this framework the eigenvector approach of the AHP is chosen for criteria weighting. The S-AHP accounts for the uncertainty and complexity associated with the values representing the relative importance while creating a sensitive evaluation of the consistency in judgments. The system allows the user to define the benefits of the criteria that are important to them, so that an appropriate treatment can be found for the deteriorated structure. The system was then tested to ensure that the model can be used in a practical environment.

One of the key strength of the system is that the main model can be applied to other types of civil infrastructure such as dams, tunnels, pavements and buildings.

As a subsequent outcome of this study, several areas have been identified to require further research and development, in order to improve the versatility and practical application of the system. The recommendations for future study are to:

- Extend the capabilities of the proposed system to consider impact damage, as this deterioration mechanism is often encountered by engineers and bridge inspectors. This would further enhance the usefulness of the system as an integrated leaning and accountability tool.
- Incorporate relevant standards and procedures used during the rehabilitation process with the recommendation. This would require the system to consider a broader range of site specific constraints, to ensure all relevant policies were addressed. Additionally, the system would need to be reviewed on a consistent basis to guarantee superseded standards and policies were updated, to avoid possible litigation for misuse.
- Recommend available materials for each concept that are compatible with the existing. This would require additional information being entered into the system about the current bridge structure. A review of these materials would need to be conducted on a regular basis to ensure they meet current industry practice.

In summary, the DSS developed as part of this research offers reliable recommendations for the selection of remediation concepts, in response to the deterioration of steel bridges. Thus, the system can not only provide assurance to project stakeholders, but can be introduced as an accelerated learning tool for novice engineers. Furthermore, should additional study in this area be conducted, and the recommendations as above implemented, the DSS can become an effective tool to optimise the strategies undertaken by road authorities, to counter increasing deterioration on aging steel bridges.

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