CONCRETE BRIDGE CONDITION ASSESSMENTS FOR MAINTENANCE PRIORITIZATION AND FUNDS ALLOCATION IN TANZANIA

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ABSTRACT

Bridge condition assessment is the process of determining the extent and severity of defects on bridge elements. The defects found are quantified in terms of indices. Several bridge Authorities use bridge indices to plan and prioritize maintenance activities. For this study, the inventory of the bridge elements and defects for four bridges: Kikwete bridge located in Kigoma, Mvomero bridge located in Morogoro, Unkuku bridge located in Dodoma, and Nyahua bridge located in Tabora Tanzania was conducted.

The results of critical bridge condition indices (BCIs) are 1.42 for the Unkuku bridge, 1.04 for the Nyahua bridge, 1.01 for the Mvomero bridge, and 0.97 for the Kikwete bridge. The total BCI of each bridge is 2.84 for Unkuku, 3.17 for Nyahua, 1.01 for Mvomero, and 5.74 for Kikwete.

In this study, the critical BCI for bridge units at the network level has been used to prioritize maintenance for major repair and the total for all condition indices of each unit of a bridge has been used for preventive maintenance funds allocation in a network. Therefore, for the bridge major repair plan, priority is given to Unkuku followed by Nyahua, Mvomero, and lastly to Kikwete.

In developing countries like Tanzania, most bridge Authorities have limited funds for bridge maintenance on which the available funds need to be proportioned. For this study, the percentage of funds allocated for maintenance of each bridge has been determined based on their total condition indices at the network level which are 48.5% for Kikwete bridge, 22.3% for Nyahua bridge, 20.2% for Unkuku and 9.0% for Mvomero bridge.

Bridge Authorities need to consider bridge maintenance prioritization and fund allocations at the network level in their bridge maintenance manual to plan for limited available resources.

Keywords: Bridge elements, inventory, defects, maintenance prioritization, bridge condition index, budget allocation.

1. INTRODUCTION

A bridge is a structure that crosses rivers, valleys, lakes, and the like. It connects transportation facilities such as roadways, railways and footpaths (Gonzalez et al., 2020). The country's economic growth and sustainability are influenced by connected transportation systems through well-designed and maintained bridges (Darban et al., 2020). The land transportation system encompasses many infrastructures such as roads, bridges and railways. Bridges perform an essential role in connecting two or more parts of roadways or railways for the smooth flow of transportation modes (Jeong et al., 2018).

Due to traffic loading and weather effects, the Bridge elements get defective and deteriorate with time. Maintenance of defects found on Bridge elements is necessary to ensure long life and smooth communication between parts connected by the bridge (Valenzuela et al., 2010). Several defects may occur to the bridge elements which include cracks, dilapidation, contamination, deformation and loss of capacity to resist loads (Fazal, 2005). The defects are assessed and analyzed to determine the current condition of the bridge (Omar and Nehdi, 2018) the maintenance of it will be to prevent the bridge from further deterioration or to perform a major repair to restore the bridge element functionality. The condition assessment of the bridge elements is the process that aims at determining the extent and severity of damages and predicting the safety of the bridge over a specified remaining service life (Omar, 2018).

The judgment of a maintenance strategy and fund allocations are mainly depending on the correctness of the condition assessments. In this regard, some bridge Authorities have established their methodologies as a guideline for bridge inspection and condition rating (Eden, 2018, Rashidi and Gibson, 2012). However, many bridge Authorities especially in developing countries like Tanzania have limited financial resources to cater to the complete maintenance of defective bridges at network levels (Darban et al., 2020). Due to this, there is a need to determine the level of deterioration of each bridge so as to decide which bridge is to be rectified first by considering the few available resources (Valenzuela et al., 2010). Therefore, most bridge Authorities confine themselves to some bridges and tend to neglect others, which leads to further deterioration of the facilities (Zhao and Tomm, 2018). The researchers have suggested that the bridge Authorities should develop methods to help decision-making by considering certain factors for maintenance prioritization and fund allocation, this is because limited resources could affect one's willingness and present biased decisions on maintenance and repair prioritization options (Carvalho et al., 2016, Rui et al., 2019).

In Tanzania, there are four main bridge Authorities responsible for bridge maintenance which are Tanzania National Roads Agency (TANROADS), Tanzania Rural and Urban Roads Agency (TARURA), Tanzania Railway Corporation (TRC), and Tanzania and Zambia Railway Authority (TAZARA). TANROADS is responsible for the Trunk and Regional roads, TARURA deals with the District roads, TRC deals with the railway network owned by Tanzania, and TAZARA deals with the railway network owned by Tanzania and Zambia. The Tanzania guideline for assessing and rating conditions of existing bridges uses an element-based inspection technique on which the guideline uses four-element level indexes which are, 1, 2, 3 & 4 and four condition states which are minor, slight, serious and critical damage (TANROADS and NPRA, 2007). But also, the guideline uses four letters which are C, T, M, and E to indicate damage consequences on bridge elements. The letter "C" signifies damage or defect affecting carrying capacity, the letter "T" damages affecting traffic safety, the letter "M" damages affecting maintenance cost only, and the letter "E" damages affecting the environment/aesthetics of the bridge elements (TANROADS and NPRA, 2007).

The bridge Authorities should have well-planned bridge damage inventories and inspection systems that will reduce fixed costs and enhance efficiency at the bridge network level and not at a single bridge (Rashidi and Gibson, 2012). Several approaches to determine and express the condition of bridges have been developed by bridge Authorities and researchers on which the worst element or unit conditions are used and other researchers use the aggregation of all the defects present (Calvert et al., 2020, Dabous and Alkass, 2010). The common procedure is to measure the structural significance of each bridge element by their contribution to the overall bridge integrity and safety to come up with a single value that indicates the overall bridge condition status (Dabous and Alkass, 2010). This procedure is useful as it assists in evaluating bridge conditions in the bridge network and it can be used to prepare bridge maintenance plans and budgeting processes.

Table 1: Element significance factor (Valenzuela et al., 2010).

Element category	Element type	Element significance factor (Sf)
I	Barrier, footway, curbs, joints,	1
II	Foundation, abutment, wing wall	2
III	Deck, bearings, wearing course	3
IV	Beams, headstocks, piers	4

Several studies have been conducted to investigate the significance/importance of bridge elements (Valenzuela et al., 2010, Wang and Elhag, 2008, Deng et al., 2014). Mansour et al., (2019) used a scale of 1 to 5 to rate the importance of bridge elements on which higher numbers correspond to the most essential element. The Tanzania bridge maintenance guideline uses a scale of 1 to 4 to indicate the element significance of the bridge. This scale was adopted for the determination of Bridge Condition Indices (BCIs) for this study. Table 1 are the bridge element categories and their corresponding significance factors (Valenzuela et al., 2010).

For this study, the process of bridge condition assessment was conducted at the element level and aggregated the element conditions to a unit or grid level through segmental visual inspection and measurement of observed defects, on which the distresses were identified, measured and rated. Distress rating is the process of evaluating and classifying defects based on their impact so that priorities can be defined for immediate actions and planning for prevention or maintenance (Fazal, 2005). The bridge deterioration level is obtained by computing the bridge condition index (BCI) from aggregating the element condition index and the unit condition index. The BCI explains the condition of the whole bridge calculated from the element condition by a single numerical value (Deng et al., 2014). Different representation of the bridge condition index has been suggested by different researchers on which the critical element condition, critical unit condition and average unit conditions are used (TANROADS and NPRA, 2007, https://www.bridgestation.co.uk, 21st July, 2022). The Tanzania bridge guideline assesses bridge damages based on different bridge elements and calculation and evaluation of overall bridge adequacy are not covered in the guideline, therefore in this study, the evaluation of bridge condition is based on critical element condition (TANROADS and NPRA, 2007).

The guideline emphasizes a thorough visual inspection of the defects in all elements of a bridge structure, both above and below the water level. But also, the defects inspection and measurements can be supplemented by destructive and non-destructive testing methodology to determine the extent of the damage (TANROADS and NPRA, 2007). The tests which may be supplemented include a concrete rebound hammer, cover meter, sound waves, x - rays, concrete core samples and steel samples for laboratory testing.

The defects can be quantified manually or using modern technologies such as Light Detection and Ranging (LiDAR), which can provide bridge as-built and inventory data and the surface condition information such as location, area, and volume of defects on surfaces, undersides, and support columns (Hoensheid, 2012). Some defects that are likely to occur on bridge elements are surface delineation, cracking, scaling, spalling, carbonation, corrosion of reinforcing steel, potholes and rutting (TANROADS and NPRA, 2007, Hoensheid, 2012, Choudhury and Hasnat, 2015, Alsharqawi et al., 2016).

To make the process of defect inventory, assessment and evaluation easier, the bridge Authorities use a coding system to identify the type of bridge defects for condition assessment (TANROADS and NPRA, 2007, Bień et al., 2016, FHWA 2014). For example, the Polish Road Authority in Poland uses two-letter coding to identify the type of defect and type of construction material of elements in which the first letter represents defect type and the second letter represents a material type. In this regard, for example, the letters "CB" indicates that "C" is water leakage and "B" is concrete material (Echaveguren, T., & Dechent, P., 2019). The Tanzania guideline uses a digit coding system to indicate defects such as "203" on which "2" denotes the damage to the concrete element and "03" denotes leakage.

This study aimed at determining bridge conditions by calculating condition indices of elements and aggregating them to unit/grid/axis level. The critical units/grid conditions are considered as conditions of the bridge for maintenance prioritizations (bridge major repair) at the network level. The total conditions of all units/grids of the bridge have been used to determine percentage resource allocation in case of limited available resources for bridge preventive maintenance at the network level. However, bridge condition indices (BCIs) can be expressed as a priority index or can be integrated with other predetermined criteria to develop the priority index (Valenzuela et al., 2010, Echaveguren and Dechent, 2019). In this regard, the allocation of the maintenance budget can be calculated using the priority index. Echaveguren and Dechent (2019) used the priority index developed by Valenzuela et al., (2010) to allocate the maintenance costs.

2. INVESTIGATION OF THE BRIDGE CONDITION

The flaws in bridge elements may occur due to various causes which include faulty design, material defects, fault construction, insufficient maintenance, environment, loading and accidents (TANROADS and NPRA, 2007, Zhang et al., 2022). A bridge can be divided into substructure, superstructure and attached facilities/elements to approaches, river courses and decks. This study did not assess the defects of the attached facilities i.e. water pipes and lighting utilities. For the case of defects assessment, the bridge is divided into units/grids/axes of the main span as a reference system for damage location as indicated in figure 1 and figure 2 (TANROADS and NPRA, 2007, RHD and JICA, 2018). The division of units/axes is from abutment to pier and pier to pier for multi-span bridges and abutment to abutment for single-span bridges and they are used to identify the defects in bridge components and elements starting from the lowest chainage for longitudinal direction and from the left side to the right side for transverse direction toward the road direction. A bridge unit/grid/axis is a group of identical sections divided for easy assessment of a large structure (TANROADS and NPRA, 2007, RHD and JICA, 2018). Therefore, each unit is inspected separately to obtain the status condition of each element for a particular unit.

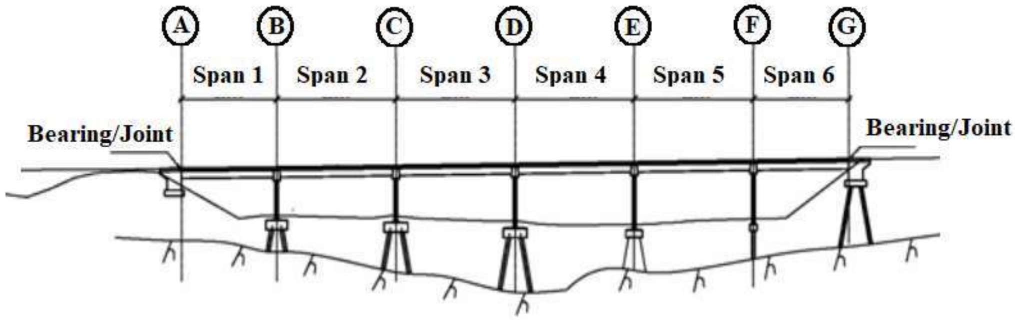

Figure 1: Showing division of axis (Axis A – G) (TANROADS and NPRA, 2007).

A bridge unit may comprise a bridge deck/slab, beams, barriers, suspenders, columns, cables, truss members, expansion joints, pedestrian walkway/sidewalk, wearing course, bearings, abutments, piers, foundations, wing walls, aprons and gabions.

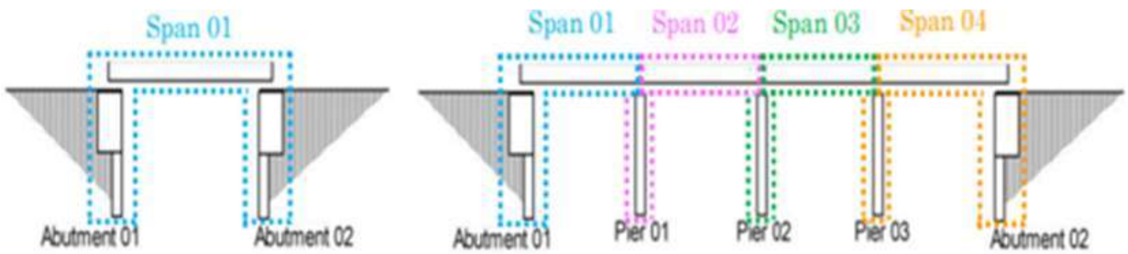

Figure 2: Common bridge-type units as indicated by span number Echaveguren and Dechent (2019)

The defects or damages to be assessed on bridge elements includes cracks, deformations, surface delineation, scaling, spalling, carbonation, corrosion of reinforcing steel, potholes and rutting. Other researchers complement visual inspection and defect analysis with automated systems for gathering and interpreting data (Valenzuela et al., 2010).

2.1 Cracks

Cracks are the common signs of structural defects, mainly in concrete, steel, stone masonry, etc. Cracks can affect surface appearance, and they can also affect structural integrity. The guideline considers the location, width, and length of cracks in the evaluation of the extent of the damage (TANROADS and NPRA, 2007). However, for the wearing course, the evaluation of cracks considers the width and size of the affected area. The guideline demonstrates that the crack width on a wearing course of up to 2 mm is ranked as a minor crack, 2 mm to 5 mm is ranked as an average crack, 5 mm to 10 mm is ranked as a big crack and more than 10 mm is ranked as critical crack (TANROADS and NPRA, 2007). However, the size of crack width for concrete materials is less than those ranked on the wearing course on which crack width less than 0.5 mm is ranked as minor, 0.5 mm to 1.0 mm is ranked as average and crack widths more than 1.0 mm are ranked as big and cracks with water leakage is ranked as critical. The transverse cracks on the load-bearing members of steel elements are evaluated as critical. For non-load-bearing elements, the evaluation is based on crack width and the extent of the damage. Other parameters like length, depth, and coverage area are not clarified (TANROADS and NPRA, 2007). Table 2 shows the cracks' widths and the ranking for field measurements and analysis.

Table 2: Cracks width and ranking (TANROADS and NPRA, 2007).

Width (*mm*)		Ranking
Masonry/Asphalt	**Concrete**	
< 2	<0.5	Minor
2 – 5	0.5 – 1.0	Average
5 – 10	>1.0	Big
>10	With Leakage	Critical

The ranking of the crack widths has been given scores as 1 for minor, 2 for average, 3 for big and 4 for critical, the scores assist in the determination of the element condition index by aggregating all damage extents and severity of the element. Table 3 are the scores for each defect ranking used to compute the condition index of the bridge element.

Table 3: Defect Condition Score (CS) corresponding to defect condition rank/state

Defect Condition state/rank	Minor	Average	Big	Critical
Defect Condition Score	1	2	3	4

2.2 Deformation

Some bridge defects have a maximum/minimum allowable limit in their condition for safety purposes which includes deflection of slabs and beams, settlements of supports, sliding and shearing of bearings (Valenzuela et al., 2010). Deformation is the change of the original intended shape, including deflection, settlement, tilting, and bridge element(s) sliding. Settlement is the vertical downward movement of bridge support elements, tilting is the movement in a sloping position, while sliding is the horizontal movement of bridge elements (TANROADS and NPRA, 2007). The evaluation of these defects considers the affected element's functionality and the extent of deformation. The extent of deformation depends on deviations from the original geometry of the bridge elements. It is mainly measured by using levelling from the reference point, although there is no boundary of the said deviations that have been set to guide the evaluation of the same during the inspection and assessment of the defects. For this study, the extent of deformation/settlement of an element is determined by using equation 1. The bridge's maximum allowable limits of deflection/tilting are taken as Span/800 for vehicular bridges and Span/1000 for Pedestrian bridges (Fu et al., 2015, AASHTO, 2008, Hwang and Le, 2014) and settlement of the bridge foundation per 30 m is taken as 13 mm (AASHTO, 2016)

$$\mathrm{PCD} = \frac{\text{Measured deformation}}{\text{Maximum allowable limit}} \mathrm{x100} \tag{1}$$

Where, PCD – is the percentage coverage of deformation

Table 4 shows the percentage range for deformations of bridge elements and the ranking for each percentage range.

Table 4. Deflection/Settlement/Tilting/Sliding and ranking

Percentage coverage of deformation (%)	Ranking
< 25	Minor
25 – 50	Average
50 – 75	Big
> 75	Critical

2.3 Potholes, Ruts, Corrugations, Depressions, Honeycombs, Carbonation and Spalling

A Pothole is a hollow on a running surface resulting from wear, a rut is the deep elongated trail that emerged due to frequent passage of the helms of automobiles and corrugation is the development of episodic crosswise undulations on road surfaces conceivably triggered by the local volume reduction of the underlying layer due to weightiness of passing vehicles (Matsuyama et al., 2020). Depression is a roadway surface area with an elevation little lower than the surrounding pavement, honeycombs are an assembly of connecting cavities or cells, and carbonation is the chemical reaction between carbon dioxide, moisture and calcium hydroxide present in cement producing calcium carbonate which lowers the concrete alkalinity (Rao and Meena, 2017). and spalling is the breakdown of concrete, rock, stone, or ore due to natural weathering or chemical reaction, or both resulting in sections of cement chipping off the main body (TANROADS and NPRA, 2007).

The potholes on the wearing course are evaluated by considering the depth and coverage area, as indicated in Table 5. This defect evaluation technic tends to ignore the dimensions of the affected elements of bridge units/grids. This is because, regardless of the dimensions of the elements of the bridge units, the same size of the potholes occurring on different dimensions of the wearing course are evaluated equally (TANROADS and NPRA, 2007).

Table 5: Pothole ranking (TANROADS and NPRA, 2007).

Depth (*mm*)	Area (cm^2)		
	< 900	**900 - 2700**	**> 2700**
< 13	Minor	Average	Big
13 - 25	Average	Big	Critical
> 25	Big	Critical	Critical

Therefore, to have relative effects of pothole depths and areas on the element, the depths and the areas of potholes in Table 5 have been converted into percentage coverage of the thickness of wearing materials and the area of the element per unit/grid. Table 6 shows the percentage coverage of depth and area of the defect on the surface of an element at a particular bridge unit/grid/axis.

Table 6: Degree of damage and defect condition state

Defected depth (%)	Defect Coverage area (DC) (%)		
	< 33	**33 - 67**	**> 67**
	Defect Condition States		
< 30	Minor	Average	Big
30 - 60	Average	Big	Critical
> 60	Big	Critical	Critical

To get the extent of pothole defect on the element, the percentage depth and percentage area are computed and the condition state is read from Table 5. Thereby the pothole condition score is obtained from Table 3 which is used to compute the aggregated condition of the element per unit/grid/axis from all defects found. This approach of determining the condition score of pothole defects has been extended to other defects which have similar occurrences on the bridge elements. The defects include ruts, corrugations, depressions, honeycombs, carbonation and spalling.

2.4 Delamination, Abrasion and Insufficient cover

Delamination is the separation of concrete strata due to insufficient adhesion between them. The evaluation of the degree of delamination on concrete elements considers the extent and location of the damage (TANROADS and NPRA, 2007). A fully developed delamination can be seen visually or detected by a hollow sound when slightly hit by a hammer. It elaborates that delamination on load-carrying elements should be given a higher degree as it affects the carrying capacity of elements than non-load-carrying elements which affects only maintenance costs. The abrasion is the scraping away of element materials due to vehicle tires as they pass over the bridge, sand and other debris carried by the river for substructure or chemical attack in the river and acidic water which dissolve the cement paste in concrete. The degree of Abrasion depends on the depth and extent of the worn-out surface (TANROADS and NPRA, 2007). The Tanzania bridge inspection guideline ranks the abrasion and delamination depths as less than 8 mm as minor damage, 8 to 15 mm as average damage, 15 to 25 mm as big damage and greater than 25 mm as critical damage (TANROADS and NPRA, 2007). For the case of this study, the depth ranges have been converted into percentages (Table 4) which should be used for other defects such as loss of concrete covers. However, in the case when the damages have covered a significant area of an element, then the degree of damage can be determined based on Table 6 and the scores are read from Table 3. The insufficient cover is the loss of thickness of the materials between the surface of embedded reinforcements and the outer surface of the concrete. On wearing cause, abrasion affects traffic safety for it polishes the surface resulting in slippage which causes an accident and affects maintenance costs when the cover of reinforcement is significantly reduced. Delamination and abrasion may result in the reduction of concrete cover and finally in corrosion of the reinforcements and the protective layer in the concrete (TANROADS and NPRA, 2007). The minimum allowable limit to be used for computing the degree of loss of concrete cover is the minimum required concrete cover as per the design requirement of the same element.

2.5 Debris, Vegetation growth and Shearing of Bearings

Vegetations are the growth of grasses and trees on the deck of the bridge, on the shoulders of traffic approaches and along the river course and banks. The vegetation obstructs visibility and reduces the road width which may cause vehicle collisions and accidents. However, the vegetation growth along the river course and banks obstructs the smooth flow of river water causing floods and even damage to bridge elements and scouring. Among of the routine maintenance works to be checked are vegetation control around the bridge, removal of debris from the wearing course, and the opening or removal of vegetation and debris from waterways (TANROADS and NPRA, 2007). This is because vegetation growth and debris may cause loss of capacity to structural elements and increased cost of maintenance. Debris is a collection of dirt and unwanted material on the bridge. It creates dampness which facilitates fungi and vegetation growth. The degree of damage depends on the extent of debris and whether any other damage has developed (TANROADS and NPRA, 2007). Debris around bearings and on-bearing itself is the course of other damages to the bearings. The damage is considered critical when the movement of bearings is hindered, and other considerations depend on whether another type of defect has emerged. Different defect types expected to occur due to debris are vegetation growth and corrosion on concrete and steel elements. Loose parts and excessive shearing on bearings may also hinder the proper function of bearings. Any loose bolts, missing bolts, nuts, or other parts, and excessive shearing of the bearings are considered critical. When the shearing of bearings is beyond the allowable maximum of 25% of the bearing thickness respectively it is also considered critical damage (TANROADS and NPRA, 2007). Therefore, the degree of damage to bearing caused by shearing can be ranked as less than 8% as minor, 8% to 15% as average, 15% to 25% as big, and greater than 25% as critical. Other consequences of excessive vegetation growth and debris/silting on bridge elements are obstruction of movements at joints, ripping of joints that cause traffic to bump, blockage of expansion joints, and continuous breaking of sealant along the joints which all are considered critical damage. Therefore, any damage to be recorded shall be assessed by considering the degree of damage and consequence (TANROADS and NPRA, 2007). For the case of this study, the degree of damage caused by debris and vegetation growth on bridge elements is computed as percentage area coverage and given a rank as per Table 4.

3. DEFECT DAMAGE CONSEQUENCE

Researchers have grouped the effects of damages to the bridge elements into four classes which are environment/aesthetic classes, structural deterioration classes, constructional/maintenance and operational/traffic passability (TANROADS and NPRA, 2007, Desnerck et al, 2018). The defects classified as environment/aesthetic are considered to affect structure appearance and are given a letter “E” while defects classified as structural deterioration are considered to affect the carrying capacity of an element and are denoted by a letter “C”, the defects classified as constructional/maintenance are considered to affect maintenance costs and are denoted by the letter “M” and the defects classified as operational/traffic passability are considered to affect smooth traffic flow across the bridge are given a letter “T” (TANROADS and NPRA, 2007).

The maintenance priority of the defects is based on the damage consequence on which the defects affecting carrying capacity are given higher priority, followed by the defects affecting smooth traffic flow, then defects affecting maintenance costs and last are the defects affecting bridge aesthetic (TANROADS and NPRA, 2007). In this regard, the weights for damage classes are not given (TANROADS and NPRA, 2007) therefore for the case of this study the weights for each damage class and defects condition scores have been proposed. Table 7 gives the weights for each damage class.

Table 7: Damage impact factors

Damage classes	E	M	T	C
Damage weights (D_w)	1.0	1.5	2.0	2.5

4. EVALUATION OF BRIDGE CONDITION

The evaluation of defects on bridges started with dividing the bridge into units/grid/axis and identifying all the elements forming the bridge units. The defects on each element were measured and recorded. The condition index of each element for a bridge unit is computed and the aggregated to bridge unit/grid condition.

4.1 Bridge Element Condition Index (BECI)

The Bridge Element Condition Index (BECI) for a given bridge unit for this study is determined by using equation 2.

$$\mathrm{BECI} = \frac{\sum_{i=1}^{n}(\mathrm{Dw_i} \ \mathrm{x} \ \mathrm{CS_i})}{\sum \mathrm{Dw_i}} \tag{2}$$

Where, Dw_i – is the damage weight corresponding to damage class (refer to Table 7)

CS_i – is the defect condition score corresponding to defect quantity/coverage (refer to Table 3).

4.2 Bridge Unit/Grid Condition Index (BUCI)

The Bridge Unit/Grid Condition Index is computed by aggregating the element condition indices of the unit and defect significant factor. For this study, equation 3 is used to compute the bridge unit condition index. The highest unit/grid condition index for a particular bridge is considered the condition of the bridge (BCI).

$$\mathrm{BUCI} = \left(\frac{\sum_{i=1}^{N}\mathrm{Sf_i}.\mathrm{BECI_i}}{\sum \mathrm{Sf_i}}\right) \tag{3}$$

Where, BUCI – is the bridge unit condition index

N – is the number of elements in a unit,

$BECI_i$ – is the element condition index

Sf_i – is the element significance factor.

5. PRIORITIZATION OF BRIDGE MAINTENANCE

A need emerged to develop a condition assessment to prioritize maintenance of the bridge structures at the network level to maintain the condition of the bridges under limited funds (Fitriani et al., 2019). The current prioritization option of bridge maintenance is based on the severity of defects and the effects of weakness on the bridge element (TANROADS and NPRA, 2007). In this regard, the most severe deficiency is given a higher priority to be maintained as the defects affect the carrying capacity of the bridge elements (TANROADS and NPRA, 2007). An overall bridge condition assessment should incorporate the flaws in all aspects to define the bridge condition status.

Table 8: Bridge condition indexes, their corresponding state, and Priority level

BCI ranges	Bridge Condition State	Priority Level
0.0 – 1.0	Good	Low
1.0 – 2.0	Fair	Medium
2.0 – 3.0	Bad	High
3.0 – 4.0	Very bad	Very High

The value of BCI obtained from equation 3 stands as the priority level for the maintenance of the bridge. Considering the bridge network, the higher the BCI, the higher the priority of the bridge to be maintained. The BCI ranges corresponding to bridge condition states and priority levels are shown in Table 8.

6. BUDGETING AND FUND ALLOCATION

Many bridge authorities have limited funds for bridge maintenance to attain the effective preventive condition of all bridges. This situation demands the prioritization of bridge maintenance and fund allocation. Abdillah et al., (2017) used the percentage of the physical condition of the bridge and traffic volume to analyze the maintenance fund allocation system. Bridge budget allocation is the process of designating funds to cover the cost of scheduled maintenance activities. Various methods are used in budgeting processes. For this study, the procedures are activity-based. It quantifies the number of rectification activities based on the extent of defected area per predefined unit cost of a specific item composing the price for all associated activities required to restore the bridge's functionality as described in TANROADS & NPRA (2007a). It will result in an un-constrained maintenance budget as per the maintenance requirement of bridges in the network. As prioritization works on the scarcity of financial resources, the total required funds for maintenance are not the same as those released for maintenance. Based on the budget released, a constrained budget being set tends to ignore some of the bridges in the maintenance program. The Minimum Fund Allocation for bridge maintenance for this study is based on the percentage of the total BUCI for the specific bridge to the total summation of BUCI of all bridges selected to be maintained after receiving the fund for bridge maintenance as shown in equation 4.

$$\mathrm{MFA} = \frac{\sum_{i=1}^{n} \mathrm{BUCI}}{\sum_{j=1}^{m} \sum_{i=1}^{n} \mathrm{BUCI}} \mathrm{TAF} \tag{4}$$

Where, MFA – is the maintenance fund allocated to a bridge
BCI – is the bridge unit/grid condition index
TAF – is the total available fund for maintenance.

7. DATA COLLECTION, ANALYSIS AND DISCUSSION

In verifying the proposed model, four bridges were selected for condition assessments and evaluation which are the Kikwete bridge located in the Kigoma region, the Mvomero bridge located in Morogoro, the Unkuku bridge located in Dodoma, and the Nyahua bridge located in Tabora. These bridges are located in different climatic zones within Tanzania's territory. Bridges in different climatic zones suffer different frequencies and intensities of natural hazards like hurricanes, heat waves, wildfires, and extreme rains (Nasr et al., 2019).

The required data were obtained from bridge site inspection, whereby visual inspection and rebound hammer test on concrete were performed to identify surface and subsurface defects on the bridge elements. The number of units and bridge lengths found for each bridge are indicated in Table 9.

Table 9: Bridge names, number of units and spans

Bridge name	Region	No. of units	Total span
Kikwete	Kigoma	11	200
Mvomero	Morogoro	1	24
Unkuku	Dodoma	3	45
Nyahua	Tabora	4	64

The observed defects were recorded in their corresponding element and bridges. Table 10 shows the defects on elements, damage weights and condition scores of the eleventh unit/grid of the Kikwete bridge which was determined to be more severely defective than other units.

Table 10: Defect quantification of bridge element for unit number 11 at Kikwete bridge

Element	Element Category	Total quantity	Units	Defect name	Defect code	Damage class	Damage weight (Dw)	Defect condition score (Cs)
Slab	III	162.5	m^2	Cracks	**211**	M	1.5	1
Beams	IV	375	m^2	Cracks	211	C	2.5	2
Curbs	I	-	-	No curbs	-	-	0	0
Bearings	III	10	No.	Blocked	709	E	1.0	1
Abutments	III	148.2	m^2	Cracks	211	M	1.5	2
Pier	IV	36.2	m^2	No defect	-	-	0	0
Headstock	IV	36.3	-	No defect	-	-	0	0
Wingwalls	II	51	m^2	Cracks	211	M	1.5	2
Foundation	II	135	m^2	No defect	-	-	0	0
Expansion joints	I	8.9	m	Blockage of joint	711	M	1.5	2
Barriers	I	112.5	m^2	Cracks	211	M	1.5	1
Wearing course	III	162.5	m^2	Cracks	601	M	1.5	1
Footway	I	60	m^2	Cracks	211	M	1.5	2

The defects were evaluated to obtain bridge element condition indices (BECI) using equation 2 and then aggregated to obtain bridge unit condition indices (BUCI) using equation 3. Table 11 shows the bridge element condition indices and bridge unit condition index for the eleventh unit of the Kikwete bridge.

Table 11: Evaluation of the critical bridge unit condition index (BUCI) for Kikwete bridge

Element	Damage weight (Dw)	Defect condition score (Cs)	Dw.Cs	BECI	Sf	BECI.Sf	BUCI
Slab	1.5	1	1.5	1	3	3	0.968
Beams	2.5	2	5.0	2	4	8	
Curbs	-	-	0	0	1	0	
Bearings	1.0	1	1.0	1	3	3	
Abutments	1.5	2	3.0	2	2	4	
Pier	-	-	0	0	4	0	
Headstock	-	-	0	0	4	0	
Wingwalls	1.5	2	3.0	2	2	4	
Foundation	-	-	0.0	0	2	0	
Expansion joints	1.5	2	3.0	2	1	2	
Barriers	1.5	1	1.5	1	1	1	
Wearing course	1.5	1	1.5	1	3	3	
Footway	1.5	2	3.0	2	1	2	
Total					**31**	**30**	

The computed bridge unit condition index for the eleventh unit of the Kikwete bridge is 0.97 which falls under good condition. The computed condition indices for other units of the Kikwete bridge are 0.64 for the first unit, 0.55 for the second unit, 0.65 for the third unit, 0.48 for the fourth unit, 0.42 for the fifth unit, 0.13 for the sixth unit, 0.14 for the seventh unit, 0.61 for the eighth unit, 0.46 for the ninth unit and 0.69 for the tenth unit. The average and total condition indices for the Kikwete bridge are 0.52 and 5.74 respectively.

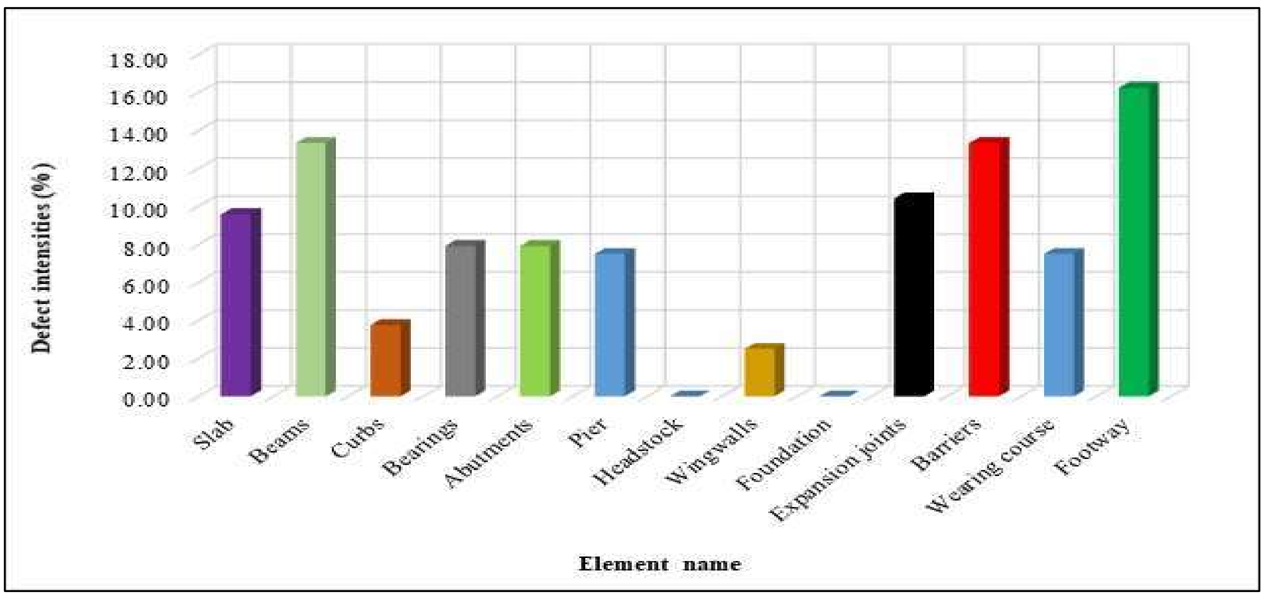

Figure 4: Defect intensities for each element of the Kikwete bridge

The major defective bridge elements at Kikwete bridge are footways with defect intensities of 16.25%, followed by beams and barriers with defect intensities of 13.33% each and expansion joints with defect intensities of 10.42%. the rest of the bridge elements have defect intensities of less than 10% which are slabs with defect intensities of 9.58%, bearings and abutments with defects intensities of 7.92% each, piers and wearing course with defect intensities of 7.50%, curbs with defect intensities of 3.75% and wing walls with defect intensities of 2.5%. The remaining element, which is the headstocks and foundation has no defects observed as indicated in figure 4. Figure 5 shows the photos of some of the defects in elements of the Kikwete bridge evaluated for this study.

Figure 5: Photos of defects for Kikwete Bridge (a) blockage by siltation and (b) cracks on a walkway

Table 12: Defect quantification of bridge element for unit number 1 at Mvomero bridge

Element	Element Category	Total quantity	Units	Defect name	Defect code	Damage class	Damage weight (Dw)	Defect condition score (Cs)
Slab	III	156	m^2	Cracks	211	C	2.5	2
Beams	IV	360	m^2	Honeycombs	202	M	1.5	3
Curbs	I	N/A	-	-	-	-	0	0
Bearings	III	5	No.	No defect	-	-	0	0
Abutments	III	142.5	m^2	Cracks	211	M	1.5	1
Pier	IV	No Pier	-	-	-	-	0	0
Headstock	IV	No headstock	-	-	-	-	0	0
Wingwalls	II	77	m^2	Cracks	211	C	2.5	2
Foundation	II	160	m^2	No defect	-	-	0	0
Expansion joints	I	17.8	m	Breaking of sealant	714	M	1.5	2
				The loose part of joint	712	T	2	2
				Blockage of joint	711	M	1.5	3
Barriers	I	108	m^2	Cracks	211	M	1.5	1

Wearing course	III	156	m^2	Cracks	601	M	1.5	1
Footway	I	57.6	m^2	Edge ripping	212	M	1.5	1

Table 12 shows the defects in elements, damage weights and condition scores of the Mvomero bridge. The Mvomero bridge is a one-span bridge and was considered as a single unit/grid.

The defects were evaluated to obtain bridge element condition indices (BECI) using equation 2 for the unit/grid and then aggregated to obtain bridge unit condition indices (BUCI) using equation 3. Table 13 shows the bridge element condition indices and bridge condition index for the Mvomero bridge.

Table 13: Evaluation of condition index (BUCI) for Mvomero bridge

Name	**Damage weight (Dw)**	**Defect condition score (Cs)**	**Dw.Cs**	**BECI**	**Sf**	**BECI.Sf**	**BUCI**
Slab	2.5	2	5	2	3	6	
Beams	1.5	3	4.5	3	4	12	
Curbs	-	-	0	0	1	0	
Bearings	-	-	0	0	3	0	
Abutments	1.5	1	1.5	1	2	2	
Pier	-	-	0	0	4	0	
Headstock	-	-	0	0	4	0	
Wingwalls	2.5	2	5	2	2	4	1.010
Foundation	-	-	0	0	2	0	
Expansion joints	1.5 2 1.5	2 2 3	3 4 4.5	2.3	1	2.3	
Barriers	1.5	1	1.5	1	1	1	
Wearing course	1.5	1	1.5	1	3	3	
Footway	1.5	1	1.5	1	1	1	
Total					**31**	**31.3**	

The computed condition index for the Mvomero bridge is 1.01 which falls under fair condition. Since the bridge has one unit then the total bridge condition index is 1.01. The major defective Bridge elements at the Mvomero bridge are the expansion joint with defect intensities of 14.94%. the remaining elements have defect intensities of less than 10% which are the wing walls and slab with defect intensities of 6.49% each, beams with defect intensities of 5.84% and wearing course, barriers, footway and abutments with defect intensities of 1.95% each. The rest elements have no defects observed. Figure 6 shows the defect intensities for each element, and Figure 7 shows the photos of the defects at the Mvomero bridge evaluated for this study.

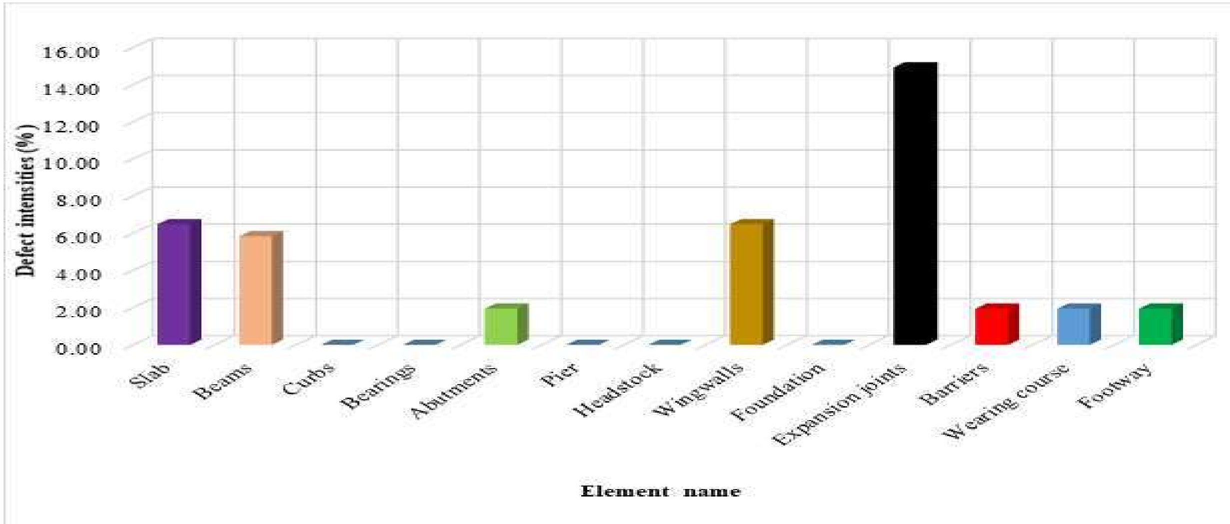

Figure 6: Defect intensities for each element of the Mvomero bridge

The Unkuku bridge has three units on which the first unit/grid was found to be the most damaged unit. Each defect was recorded to the corresponding element. Table 14 shows the defects in elements, damage weights and condition scores of the first unit/grid of the Unkuku bridge.

Table 14: Defect quantification of the first unit/grid of Unkuku bridge

Element	Element Category	Total quantity	Units	Defect name	Defect code	Damage class	Damage weight (Dw)	Defect condition score (Cs)
Slab	III	133.5	m^2	Cracks	211	M	1.5	1
				Leaking	203	C	2.5	4
Beams	1V	195	m^2	Honeycombs	202	M	1.5	1
Curbs	I	No curbs	-	-	-	-	0	0
Bearings	III	5	No.	Blocked	701	M	1.5	3
Abutments	III	22	No.	Defective weep holes	803	M	1.5	3
		79.8	m^2	Honeycombs	202	M	1.5	3
			m^2	Cracks	211	M	1.5	2
Pier	IV	No pier	-	-	-	-	0	0
Headstock	IV	N/A	-	-	-	-	0	0
Wingwalls	II	48	m^2	Honeycombs	202	M	1.5	2
Foundation	II	-	-	No defect	-	-	0	0
Expansion joints	I	8.9	m	Blockage of joint	711	M	1.5	4
Barriers	I	67.5	m^2	Cracks	211	M	1.5	2
Wearing course	III	97.5	m^2	Cracks	601	M	1.5	1
Footway	I	36	m^2	Cracks	211	C	2.5	4

Table 15 shows the bridge element condition indices and bridge unit condition index for the first unit of the Unkuku bridge.

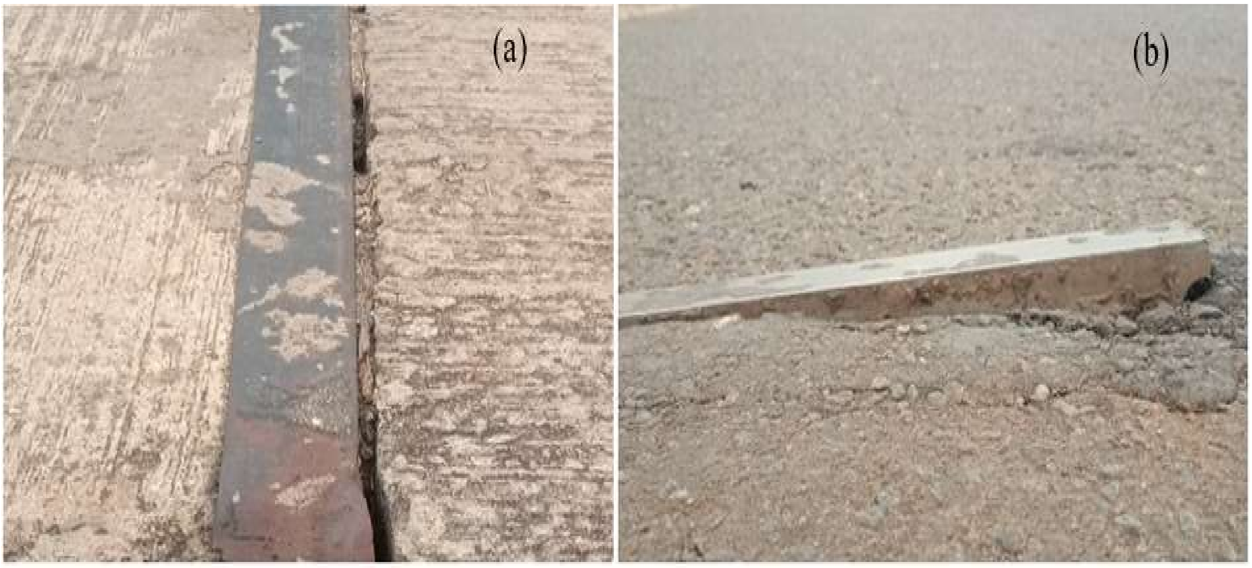

Figure 7: Photos of joint expansion defects, which are (a) Blockage by siltation and (b) Lose part of the joint for the Mvomero bridge

Table 15: Evaluation of the critical Bridge Unit Condition Index (BUCI) for the Unkuku bridge

Element	Damage weight (Dw)	Defect score (Ds)	Dw.Cs	BECI	Sf	BECI.Sf	BUCI
Slab	1.5 2.5	1 4	1.5 10	2.9	3	8.6	
Beams	1.5	1	1.5	1	4	4	
Curbs	-	-	0	0	1	0	
Bearings	1.5	3	4.5	3	3	9	
Abutments	1.5 1.5 1.5	3 3 2	4.5 4.5 3	2.7	2	5.3	
Pier	-	-	0	0	4	0	1.42
Headstock	-	-	0	0	4	0	
Wingwalls	1.5	2	3	2	2	4	
Foundation	-	-	0	0	2	0	
Expansion joints	1.5	4	6	4	1	4	
Barriers	1.5	2	3	2	1	2	
Wearing course	1.5	1	1.5	1	3	3	
Footway	2.5	4	10	4	1	4	
Total					**31**	**44.0**	

The computed bridge unit condition index for the first unit of the Unkuku bridge is 1.42 which falls under fair condition (refer to Table 8). The condition indices for other units of the Unkuku bridge are 0.61 for the second unit and 0.81 for the third unit. The average and total condition indices for the Unkuku bridge are 0.95 and 2.84 respectively. Figure 8 shows the defect intensities on elements of the Unkuku bridge evaluated for this study.

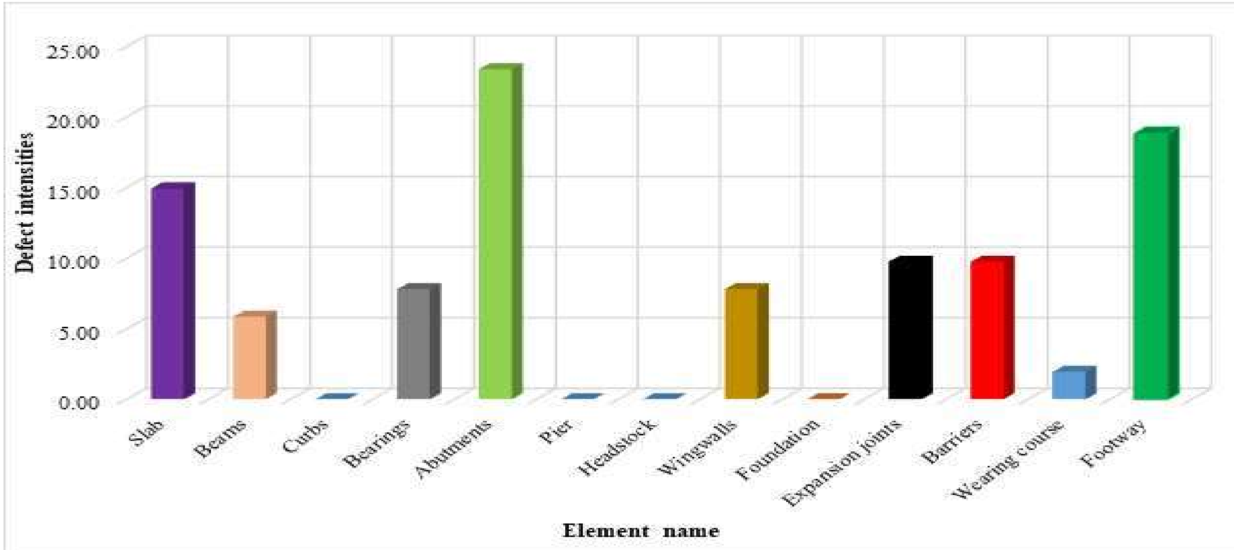

Figure 8: Defect intensities for each element of the Unkuku bridge

The major defective bridge elements at Unkuku bridge are abutment with defect intensities of 23.38%, followed by footway with defect intensities of 18.83%, and slab with defect intensities of 14.94%. The rest of the bridge elements have defect intensities of less than 10% which are expansion joints and barriers with defect intensities of 9.74 each, bearings and wing walls with defect intensities of 7.79%, beams with defect intensities of 5.84% and wearing course with defect intensities of 1.95%. Figure 9 shows the photos of the defect for the Unkuku bridge.

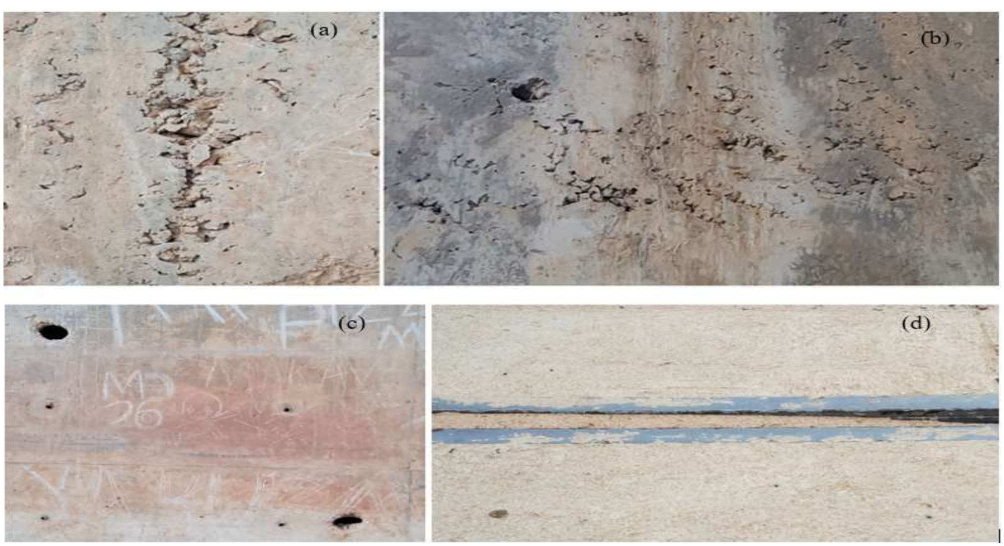

Figure 9: Photos of defects on Unkuku bridge (a) and (b) abutments honeycombs, (c) defective weep hole, and (d) blockage of expansion joint.

The Nyahua bridge has four units on which the first unit/grid was found to be the most defective unit. Each defect was recorded to the corresponding element. Table 16 shows the defects in elements, damage weights and condition scores of the first unit/grid of the Nyahua bridge.

Table 16: Evaluation of the bridge condition index (BCI) for the Nyahua bridge

Element	Element Category	Total quantity	Units	Defect name	Defect code	Damage class	Damage weight (Dw)	Defect condition score (Cs)
Slab	III	104	m^2	Cracks	211	C	2.5	1
Beams	IV	208	m^2	Honeycombs	202	C	2.5	2
Curbs	I	No curbs	-	-	-	0	0	0
Bearings	III	10	No.	No defect	-	0	0	0
Abutments	III	148.2	m^2	Honeycombs	202	M	1.5	2
				Cracks	211	E	1	1
Pier	IV	No pier	-	-	-	0	0	0
Headstock	IV	No headstock	-	-	-	0	0	0
Wingwalls	II	102	m^2	Honeycombs	211	M	1.5	3
Foundation	II	-	-	No defect	-	0	0	0
Expansion joints	I	8.9	m	Blockage of joint	711	M	1.5	4
Barriers	I	72	m^2	Ripping on edge	212	M	1.5	1
Wearing course	III	104	m^2	Depression	604	M	1.5	1
Footway	I	38.4	m^2	Cracks	14.4	M	1.5	4

Table 17 shows the bridge element condition indices and bridge unit condition index for the first unit of the Nyahua bridge. The computed bridge unit condition index for the first unit of the Nyahua bridge is 1.04 which falls under fair condition. The condition indices for other units of the Nyahua bridge are 0.82 for the second unit, 0.52 for the third unit, and 0.79 for the fourth unit. The average and total condition indices for the Nyahua bridge are 0.79 and 3.17 respectively.

Table 17: Evaluation of the critical Bridge Unit Condition Index (BUCI) for Nyahua bridges

Element	Damage weight (Dw)	Defect condition score (Cs)	Dw.Cs	BECI	Sf	BECI.Sf	BUCI
Slab	2.5	1	2.5	1	3	3	
Beams	2.5	2	5	2	4	8	
Curbs	0	0	0	0	1	0	
Bearings	0	0	0	0	3	0	
Abutments	1.5	2	3	1.6	2	3.2	1.04
	1	1	1				
Pier	0	0	0	0	4	0	
Headstock	0	0	0	0	4	0	
Wingwalls	1.5	3	4.5	3	2	6	
Foundation	0	0	0	0	2	0	

Expansion joints	1.5	4	6	4	1	4
Barriers	1.5	1	1.5	1	1	1
Wearing course	1.5	1	1.5	1	3	3
Footway	1.5	4	6	4	1	4
Total					**31**	**32.2**

The major defective bridge elements at Nyahua bridge are abutment with defects intensities of 20.92% followed by footway with defects intensities of 16.74%, beams with defect intensities of 13.25%, expansion joint with defect intensities of 12.55%, wing walls with defect intensities of 10.74% and barriers with defect intensities of 10.46%. o barriers and wearing course with defects intensities of 0.100 each. The rest of the bridge elements have defect intensities of less than 10% which are bridge bearings and wearing course with defect intensities of 4.18% each. The remaining elements have no defects observed. Figure 10 shows the defects intensities for each element of the Nyahua Bridge and Figure 11 is the photos of defects on the Nyahua bridge.

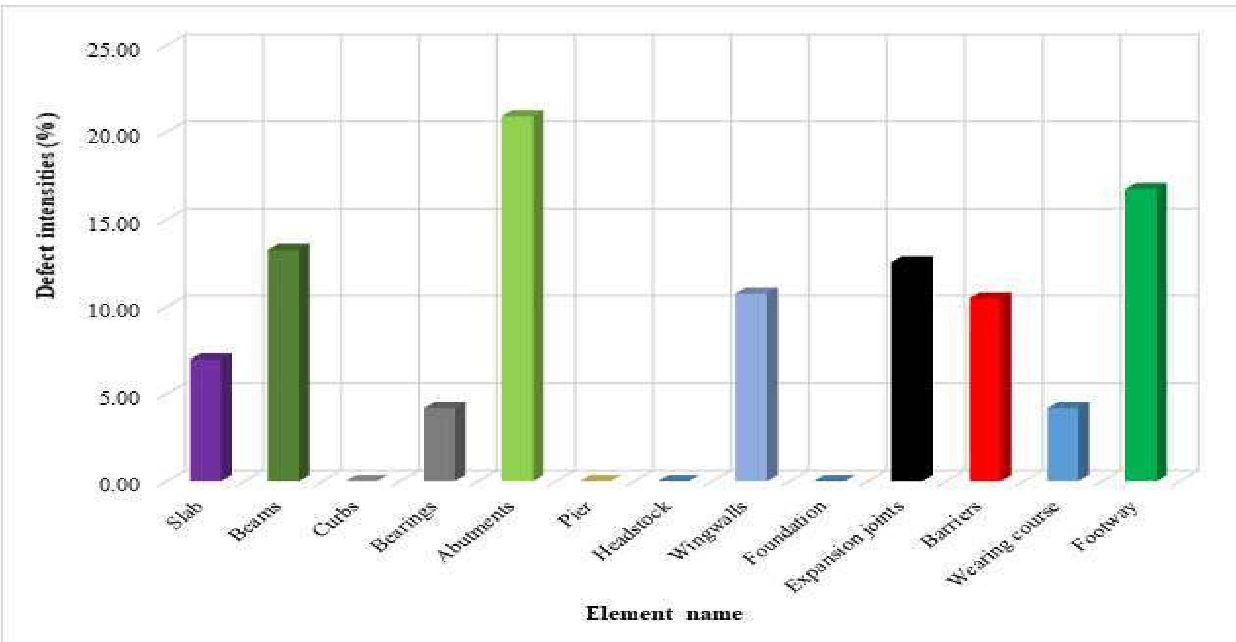

Figure 10: Defect intensities for each element of the Nyahua Bridge

The evaluation of the critical bridge unit condition of four bridges indicates that the condition index of Kikwete bridge is 0.968, Mvomero bridge is 1.010, Unkuku bridge is 1.418 and Nyahua bridge is 1.039. These results signify that the Unkuku bridge is more defective than other bridges followed by the Nyahua bridge, Mvomero bridge and lastly Kikwete bridge.

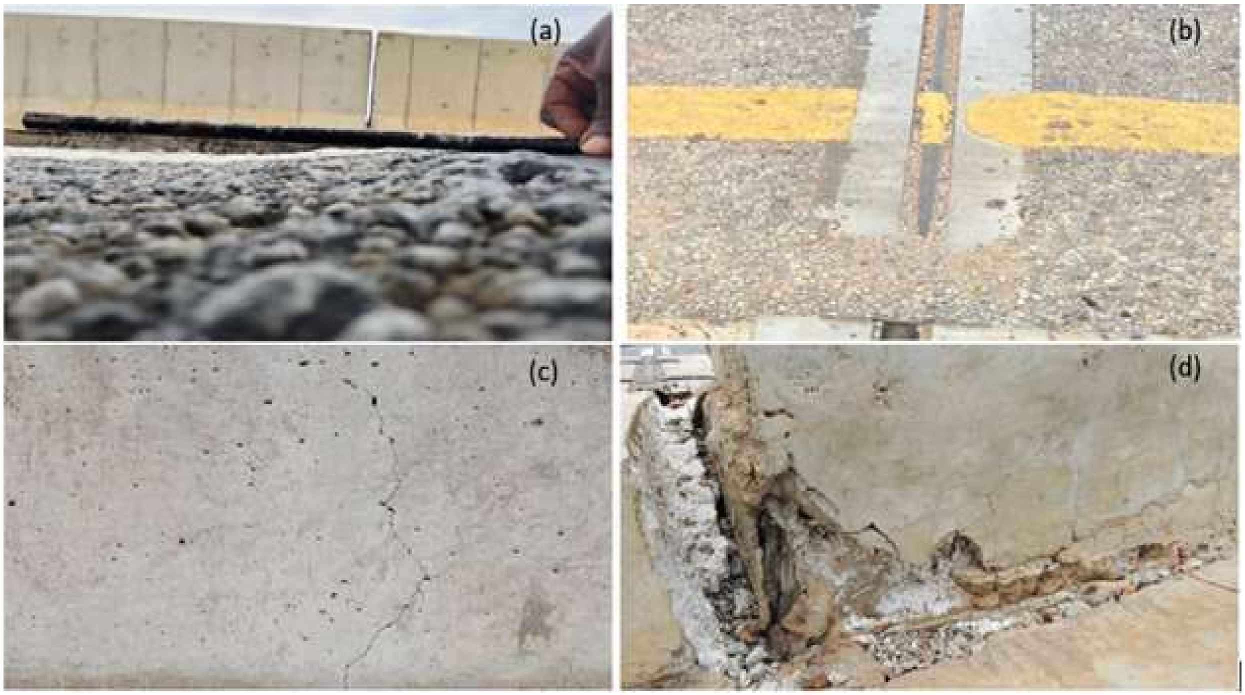

Figure 11: Photos of defects on Nyahua bridge (a) wearing course depression (b) blockage of expansion joints by iron welding and siltation, (c) cracks on the abutment, and (d) edge ripping on barrier wall (concrete parapet)

Table 18 shows all bridge unit condition indices for all units, total, average and critical BUCI. The critical BUCI is considered as a Bridge Condition Index (BCI) for the bridge.

Table 18: Bridge Unit Condition Index, total, average and critical BUCI

Bridge name	Bridge Unit/grid											Total BUCI (For funds allocation of Preventive Repairs)	Average BUCI	Critical BUCI (For prioritization of Major Repairs)
	1	2	3	4	5	6	7	8	9	10	11			
Kikwete	0.64	0.55	0.65	0.48	0.42	0.13	0.14	0.61	0.46	0.69	0.97	5.74	0.52	0.97
Mvomero	1.01											1.01	1.01	1.01
Unkuku	1.42	0.61	0.81									2.84	0.95	1.42
Nyahua	1.04	0.82	0.52	0.79								3.17	0.79	1.04

7.1 Maintenance Prioritization for Bridge Major Repairs

The maintenance funds allocation for major repairs, should not necessarily be distributed to all evaluated bridges. It should consider covering the required amount of funds for the Unkuku bridge first then followed by the Nyahua bridge, Mvomero bridge, and lastly Kikwete bridge which has a Bridge Condition Index of 1.42, 1.04, 1.01 and 0.97 respectively. Figure 12 shows the bridge condition indices of the four bridges. For this study, the lower the index value, the better the bridge's condition. This is different from other studies in which the higher value of indices indicated the better conditions of the facilities assessed (Darban et al., 2020, Mansour et al., 2019)

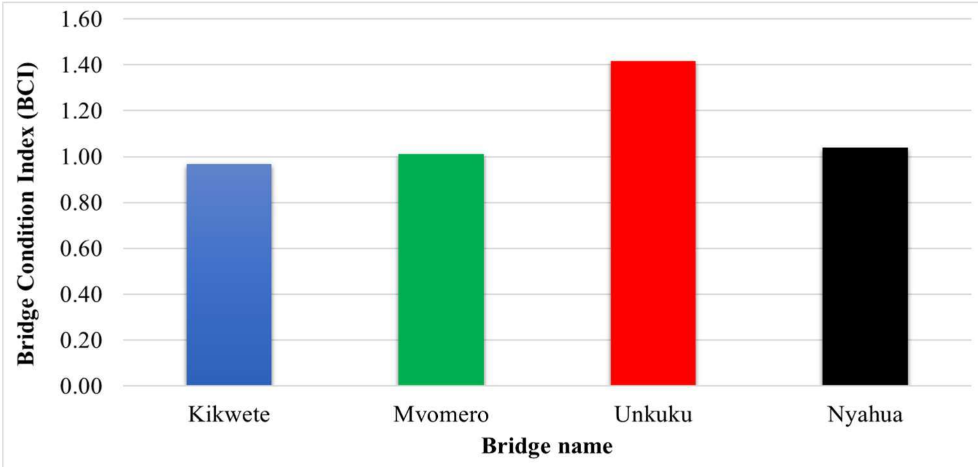

Figure 12: Critical Bridge Condition Indices

Based on Table 8 and the BCIs obtained for all bridges, the priority level of the Kikwete bridge falls at the low level and the remaining three fall at the medium level. However, the priority level differs among them as per BCI, as indicated in Figure 12. For this study, the higher the BCI, the higher the priority for the maintenance of the bridge. Therefore, based on Figure 12, the Unkuku bridge has a higher priority in maintenance for major repair, than other bridges, followed by Nyahua, Mvomero and at the end Kikwete bridges.

Based on the priority level among bridges and funds available, the allocation of maintenance funds for bridge major repair will depend on the number of scenarios which will be equal to the number of bridges considered for maintenance. This study covers four bridges and therefore there are four scenarios for funds allocation as shown in Table 19. Table 19 indicates that, until full requirements for major repair of a bridge with the highest priority are met, is when the bridge with next highest priority can be allocated funds.

Table 19: Bridge Major Repair Funds Allocation (MRFA) Scenarios

Priority	Bridge Name	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	Unkuku	Full/Partial	Full	Full	Full
2	Nyahua		Full/Partial	Full	Full
3	Mvomero			Full/Partial	Full
4	Kikwete				Full/Partial

7.2 Maintenance Fund Allocation for Bridge Preventive Maintenance

The total available funds for bridge preventive maintenance (Routine Maintenance) should be distributed for rectifying all bridges in a network. Fund allocation for bridge preventive should be as per Equation 5. Table 20 shows the total BUCI and percentage of Preventive Maintenance Funds Allocation (PMFA) for each bridge.

Table 20: Total Bridge Unit Condition Index for all units and Preventive Maintenance Funds Allocation for each bridge

Bridge Name	Total BUCI	PMFA (% of TAF)
Kikwete	5.74	44.98
Nyahua	3.17	24.84
Unkuku	2.84	22.26
Mvomero	1.01	7.92
Total BCI for all bridges	**12.76**	**100.00**

7.3 Total Maintenance Funds Allocation (TMFA)

The total maintenance funds allocation is a total of the bridge's major repair and preventive maintenance funds as shown in Equation 5.

$$\begin{bmatrix}\text{Total Maintenance}\\ \text{Funds Allocation}\end{bmatrix} = \begin{bmatrix}\text{Preventive Maintenance}\\ \text{Funds Allocation}\end{bmatrix} + \begin{bmatrix}\text{Major Repair}\\ \text{Funds Allocation}\end{bmatrix}$$

$$\text{TMFA} = \text{PMFA} + \text{MRFA} \qquad (5)$$

8. CONCLUSION

This study has been conducted to improve bridge inspection methodology for measuring and rating the defects by dividing the bridge into several units according to the number of spans present. It incorporates into the guideline the calculation to obtain the BCI of each unit. The BCI of the worst unit is taken to represent the overall concrete bridge conditions and be used to rank the maintenance priority for major repairs. The worst bridge condition for major repairs for each bridge is 0.97 found at the 11th unit of the Kikwete, 1.01 for Mvomero, 1.42 found at the 1st unit of the Unkuku and 1.04 found at the 1st unit of the Nyahua bridges. According to the worst conditions found, the Unkuku bridge should be given higher priority in maintenance for major repairs than other bridges followed by Nyahua, Mvomero, and lastly Kikwete bridges.

The percentage of preventive maintenance funds allocation for each bridge was found to be 44.96%, 7.93%, 22.26% and 24.84% of the total available funds for preventive maintenance for Kikwete bridge, Mvomero bridge, Unkuku bridge and Nyahua bridge respectively. Based on the percentage of the preventive maintenance funds allocated, Kikwete bridge has a higher amount followed by Nyahua, Unkuku and lastly Mvomero bridges.

This study will help the bridge authorities during inspections of bridges, budgeting, and maintenance programs under shortage of financial resources for bridge maintenance. However, not all bridges can be rectified simultaneously in the scarcity of resources and funds. Therefore, a prioritisation tool has been provided for use to assess in detail the defects and determine the conditions of bridges within the road network, that is it can be used as a selection and budgetary tool for bridge managers to decide which bridge to be rectified first and what maintenance is required under limited resources.

9. RECOMMENDATION

The four bridges analyzed to determine their condition indices were selected based on different climatic zones and seismic zones in Tanzania. This is because floods and seismic effects also contribute to bridge failure. In this regard, the next study is recommended incorporating bridge failure/damage risk factors which are flooding, seismic and scouring potentials as the cause and acceleration of defects on bridge maintenance prioritization options.

DECLARATIONS

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Conflict of interest

The authors declare no conflict of interest.

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