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An Age- and Condition-dependent Variable Weight Model for Performance Evaluation of Bridge Systems

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An Age- and Condition-dependent Variable Weight Model for Performance Evaluation of Bridge Systems

Yuan Ren, Xiang Xu*, Bin Liu, and Qiao Huang

ABSTRACT

To address the balance problem between indexes within the performance evaluation of bridge systems, this paper develops an age- and condition-based variable weight model (ACVWM). First, the limitations of existing models used for the multi-layer weighted sum method, *i.e.*, constant weight model (CWM) and condition-based variable weight model (CVWM), are presented through case studies, indicating that the weight variation is insufficient to characterize the deterioration law of components. Then, the definition of age-based variable weight is established following the existing concept of condition-based variable weight, which makes weights vary with service ages. Considering the characteristics of bridge assessment, an age-based variable weight model is built up to depict the time-variant trends of index weights with the service age. The variation law of age-based variable weight is discussed by using indexes in the superstructure of suspension bridges. As a result, the weights of replaceable and permanent components behave differently within the bridge service life. Finally, the ACVWM is built up and its effectiveness is verified through the same case studies applied to the CWM and CVWM. Compared with the evaluation results from the CWM and CVWM, the evaluation result of the ACVWM is more in line with the real maintenance strategy. Considering the CVWM in which low initial weights may lead to unsatisfactory weight assignment, the advantage of the proposed ACVWM lies in its capability to adjust initial weights over the service age.

Keywords: bridge evaluation; variable weight; condition-based variable weight model; age-based variable weight model; maintenance strategy

1. INTRODUCTION

Performance evaluation of in-service bridges, especially large-scale bridges, is a critical and sophisticated systematic project for the bridge maintenance and management (Chen et al., 2020; Liu et al., 2009; Yang et al., 2019). Abundant existing research works have been presented, including condition evaluation (Bolar, 2013; Gattulli and Chiaramonte, 2005), reliability assessment (Frangopol et al., 2008; Xia et al., 2012; Liu et al., 2017; Liu et al., 2020), and load testing evaluation (Caglayan et al., 2012; Faber et al., 2000).

Considering the structural complexity and uncertainty, analytic hierarchy process (AHP) is always applied for performance assessment of existing bridges, which is an efficient decision making tool for complicated problems with multiple criteria (Rashidi et al., 2017; Sasmal and Ramanjaneyulu, 2008). MOT (2015a) took advantages of AHP to evaluate bridge performance, where bridge structures were decomposed into three layers (i.e., system, component and element layers) and the weighted sum algorithm was used to form a comprehensive evaluation result. Liang et al. (2001) set up a multiple layer fuzzy method for evaluating the damage stage of existing reinforced concrete bridges, where four actual bridges were applied to verify the effectiveness of the proposed model. Sasmal and Ramanjaneyulu (2008) developed a systematic procedure and formulations for condition evaluation of existing bridges using AHP in a fuzzy environment, where the method would help engineers and policy makers concerned with bridge management to overcome the problem related to prioritization and decision on funding related to rehabilitation of bridges. Li et al. (2011) proposed a hierarchical structure for synthetic rating of each structural component by using measurements from structural health monitoring (SHM) system, where the evaluation result could help make decisions of inspection policy. Yang et al. (2019) presented a comprehensive condition assessment of long-span pre-stressed concrete continuous box-girder bridges, where the original interval evidence theory-based fuzzy AHP approach was employed. Rashidi, Samali, and Sharafi (2016a, 2016b) proposed a systematic study for condition assessment and priority ranking of bridges using AHP, where the priority index was created for owners to understand and compare the overall condition of multiple bridges within the transport networks.

The aforementioned studies play a crucial role in practical maintenance and management of bridges, however constant weight model (CWM) used in the AHP evaluation framework may lead to some unacceptable decision-makings (Xu et al., 2018). In essence, the weight subject to the index reflects the importance of the signature index to the overall performance of bridges. Since the CWM ignores the weight-varying features, the evaluation result derived from CWM sometimes will be unreasonable.

In view of the limitation of the CWM in balance problem between indexes, Liu (1997) proposed a systematic definition of condition-based variable weight model (CVWM), where the weight varied with the condition of the index. Then, CVWMs were widely applied to diverse disciplines for performance evaluation and decision makings. Wu et al. (2016) proposed a variable weight model to evaluate the dynamic processes involved in groundwater inrushes, which could reflect the influence of index value mutates with changes in hydrogeogical conditions. Yao and Ma (2012) used the variable weight model for hydraulic projects tendering evaluation, where the weight will change with the evaluating value to make more credible and scientific decisions. Li et al. (2017) presented an integrative fuzzy variable evaluation model based on fuzzy theory and variable weights to measure variations in water quality, where variable weight model fully considered the influences of extremely poor indices on overall water quality. Chen et al. (2015) took advantages of equilibrium variable weight to adjust the constant weight under extreme cases for comprehensive performance assessment of wireless sensor network. Xu et al. (2018) used local variable weight model for condition assessment of suspension bridges to model the scenario that severe localized deficiency leads to significant reduction of overall performance of bridges.

With the application of CVWMs, the balance issue within indexes is well addressed to achieve rational evaluation results. Moreover, owing to the uncertainty and inaccuracy of existing technologies in inspecting structural internal defects and the difficulty in accessing to positions to implement inspections, the physical condition of the bridge is impossible to be thorough known. In this regard, condition-based evaluation method derived from existing inspection information always indicate a better situation than the actual ones due the unseen degradations.

In addition to the index condition, the evaluation index also has time attributes for bridge performance evaluation. In the practical maintenance and management activity of infrastructures, priorities will change with the service age of bridges. More attention should be paid to the component approaching its service life since the component tends to have a larger functional failure probability. For instance, if the bridge has serviced for almost 15 years, the priority of the maintenance policy should focus on bearings, whose design service life is 15 years. To satisfy the time-varying demand, age-dependent variable weight model (AVWM) is developed and introduced to make evaluation result in consistent with the actual priority during maintenance activity. Moreover, the AVWM is a supplement to the condition-based bridge performance evaluation method to model the unseen performance degradations in a general way. Xu et al. (2019) introduced the AVWM to evaluate comprehensive condition of suspension bridges for maintenance, repair and rehabilitation, whereas, the AVWM is established within the particular framework for suspension bridges and the comparisons between the CWM and CVWM is insufficient.

In this paper, the AVWM is applied to a more general framework in MOT (2011) to extend its applications. First, the limitations of CWM and CVWM for bridge performance evaluations are illustrated through case studies. Subsequently, the AVWM is briefly introduced following the concept of CVWM, and further combined with CVWM to formulate the age- and condition-dependent variable weight model (ACVWM), where the weight in the model varies with both the index condition and service age. Finally, the aforementioned case study is used to verify the effectiveness of the proposed ACVWM.

2. DISCUSSION ON CWM AND CVWM

2.1 Introduction of CWM and CVWM

The CWM is a common method for decision making, and it is expressed as

$$V_C = \sum_{j=1}^{m} \omega_j^0 x_j, \left(\sum_{j=1}^{m} \omega_j^0 = 1 \right) \tag{1}$$

where m is the number of indictors; ω_j^0 is the constant weight of the j^{th} indicator, whose value varies between 0 and 1; and x_j is the condition value of the j^{th} indicator.

In view of the limitations of CWM in balance issue, CVWM was developed that enables weights to vary with the condition of indicators (Liu, 1997). The idea of the CVWM is to make weights vary with the condition values of indicators, which is in line with the actual situation that the importance of the indicator (*i.e.*, weight) is subject to the index condition. For instance, the importance of a certain element of a structure will increase with its deterioration grade. A systematic definition of condition-based variable weight was proposed as follows:

Definition 1: Let $\mathrm{W}(\mathrm{X}) = (\omega_1(\mathrm{X}), \omega_2(\mathrm{X}), \cdots, \omega_m(\mathrm{X}))$ meet the 3 conditions:

(1) Normality: $\sum_{j=1}^{m} \omega_j(\mathrm{X}) = 1$;

(2) Continuity: $\omega_j(\mathrm{X})$ is continuous with each index condition; and

(3) Penalty: $\omega_j(\mathrm{X})$ is monotonically decreasing with respect to x_j.

where $\mathrm{W}(\mathrm{X})$ is a set of m-dimensional variable weight vector; and $\mathrm{X} = (x_1, x_2, \dots, x_m)$, in which x_i is the condition value of the index.

In general, balanced functions are always built up in advance instead of constructing the variable weight vector directly. A variable weight ω_j could be illustrated by using the balanced function *B* as

$$\omega_j = \frac{\omega_j^0 \dfrac{\partial B}{\partial x_j}}{\sum_{k=1}^{m} \omega_k^0 \dfrac{\partial B}{\partial x_k}} \tag{2}$$

The popular balanced functions include sum and product types, which are

Sum type $$B_S = \sum_{j=1}^{m} x_j^{\alpha_s}, \text{ for } 0 \le \alpha_s \le 1 \tag{3}$$

Product type $$B_P = \prod_{j=1}^{m} x_j^{\alpha_s}, \text{ for } \alpha_s > 0 \tag{4}$$

where α_s is a condition-based parameter which dominates weight adjustment.

The sum type balanced function is widely used for condition assessment of structures. The typical CVWM by using the sum type balanced function is expressed as

$$V_S = \sum_{j=1}^{m} \omega_j x_j = \sum_{j=1}^{m} \frac{\omega_j^0 x_j^{\alpha_s}}{\sum_{k=1}^{m} \omega_k^0 x_k^{\alpha_s - 1}}, \text{ for } 0 \le \alpha_s \le 1 \tag{5}$$

2.2 Limitations of CWM and CVWM

In view of the limitations of the CWM, Lan and Shi (2001) incorporated the variable weight theory into the condition evaluation of bridges, where the sum type balanced function was employed and the condition-based parameter α_s was set as 0.5. However, challenges arise in practical engineering applications when applying the CVWM, which will be illustrated through a case study.

In-situ inspection information of a suspension bridge is used for condition evaluation via both the CWM and CVWM. First, a multi-layer framework of suspension bridges for performance evaluation, as shown in Fig. 1, is adopted referring to MOT (2011). Herein, the condition values of component indicators are calculated by using the rules in MOT (2011). In particular, the condition value of component indicator (*x*) are calculated by

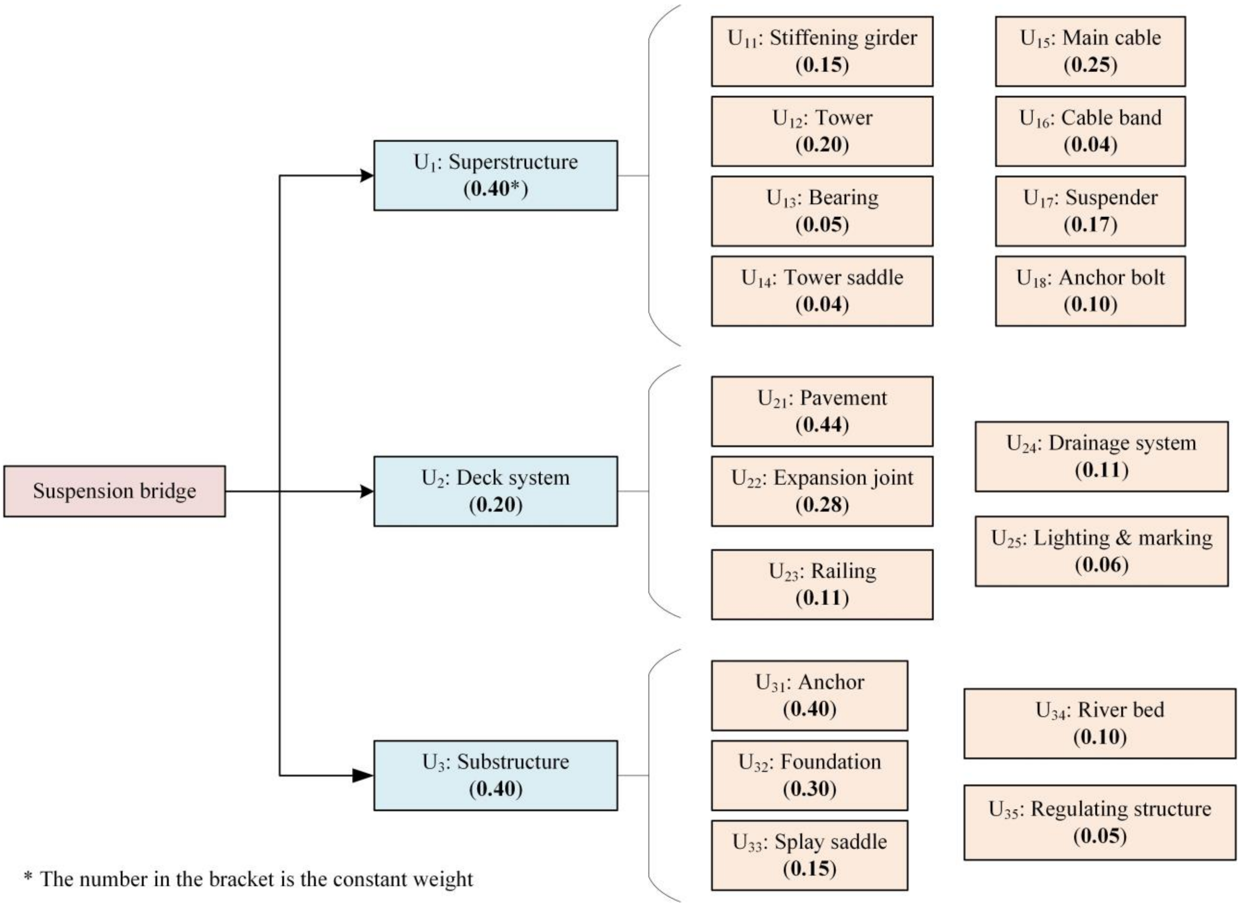
$$x = 100 - \sum_{i=1}^{n} T_i \tag{6}$$

when $i = 1$ $$T_1 = DP_1$$

when $i \geq 2$ $$T_i = \frac{DP_i}{100 \times \sqrt{i}} \times \left(100 - \sum_{j=1}^{i-1} T_j\right)$$

when $DP_i = 100$ $$x = 0$$

where n is the number of defects with respect to the component; DP_i is the deduction point associated with the i^{th} defect, which could be found from the evaluation criteria in MOT (2011) (*e.g.*, deterioration of main cable coating as listed in Table 1); and T_i is the conversion value of DP_i, which is used to deal with the situation where multiple defects accompany with the same component.



* The number in the bracket is the constant weight

Fig. 1 Multi-layer framework of suspension bridges

Table 1 Evaluation criterion regarding deterioration of main cable coating

Grade	Qualitative description	Quantitative description	*DP*
1	Excellent condition	-	0
2	Individual damage, aging and water seepage	Deterioration area less than 1% of the total coating area	25
3	Localized damage, aging and water seepage	Deterioration area less than 10% of the total coating area	40
4	Serious damage, aging and water seepage	Deterioration area larger than 10% of the total coating area	50

Detailed inspection results of the studied suspension bridge are listed in Table 2. On the whole, the condition of the suspension bridge is acceptable except for the suspender, whose cover was damaged seriously and the surface of the wires was deeply corroded. In order to avoid the hidden threaten to the operational and structural safety of the bridge, experts decided to replace the damaged suspender.

Table 2 Field inspection results of the suspension bridge

System	Component	Defect description
Superstructure	Stiffening girder	Slight coating cracking occurred at the rib-to-deck weld joints, whose area less than the total area of the component.
	Bearing	Degradation of paint film on support surface; There was a small amount of PTFE powder around the bearing.
	Cable band	Individual cable band coating deterioration.
	Suspender	Some anchors had slight water seepage and damage; The sheath of a suspender was damaged seriously, and the surface steel wire was deeply corroded.
Deck system	Pavement	Cracks and damage appeared in the pavement.
	Expansion joint	Hollow in the north expansion joint; Local corrosion in both the north and south expansion joints.
Substructure	Anchor	Slight water leakage; North anchor chamber had cracks.

Based on the inspection results and Eq. (6), the evaluation process by using the CWM and CVWM is listed in Table 3, where the CVWM is the classical one as defined in Eq. (5).

Table 3 Evaluation process by using the CWM and CVWM

System	Component	Condition value	Constant weight	Condition-based variable weight*
Superstructure	U_{11}	75.00	0.15	0.141
U_1	U_{12}	100.00	0.20	0.163

System	Component	Condition value	Constant weight	Condition-based variable weight*
	U_{13}	75.00	0.05	0.047
	U_{14}	100.00	0.04	0.033
	U_{15}	100.00	0.25	0.203
	U_{16}	85.12	0.04	0.035
	U_{17}	21.75	0.17	0.297
	U_{18}	100.00	0.10	0.081
Deck system U_2	U_{21}	61.74	0.44	0.479
	U_{22}	72.50	0.28	0.281
	U_{23}	100.00	0.11	0.094
	U_{24}	100.00	0.11	0.094
	U_{25}	100.00	0.06	0.052
Substructure U_3	U_{31}	78.92	0.40	0.429
	U_{32}	100.00	0.30	0.286
	U_{33}	100.00	0.15	0.143
	U_{34}	100.00	0.10	0.095
	U_{35}	100.00	0.05	0.047

*Condition-based parameter in the CVWM is 0.5.

The evaluation results of the suspension bridge are summarized in Table 4, which are calculated by using the CWM and CVWM, respectively. The grades of condition are determined based on MOT (2011), and the maintenance strategies are decided according to the grades. In detail, the specific relationship is listed in Table 5. According to Table 5, the evaluation result of the CWM (84.16) recommends minor repair; while the CVWM suggests medium repair. Whereas, the actual maintenance strategy in this case study is replacement of the damaged suspender, which belongs to the category of overhaul according to MOT (2009). Thus, the evaluation results of both the CWM and CVWM are not so satisfactory for practical applications since the recommended maintenance strategy is not in accordance with the actual one.

Table 4 Evaluation results by using CWM and CVWM

Model	Evaluation result of U_1	Evaluation result of U_2	Evaluation result of U_3	Evaluation result of the bridge	Grade of condition
CWM	81.10	75.46	91.57	84.16	I
CVWM	71.56	73.93	90.96	79.29	III

Table 5 Relationship between the grade and maintenance strategy

Grade	Evaluation interval	Maintenance strategy
I	[95,100]	Maintenance
II	[80,95)	Minor repair
III	[60,80)	Medium repair
IV	[40,60)	Overhaul
V	[0,40)	Reconstruction

The aforementioned discussions are on the basis of condition-based parameter $\alpha_s = 0.5$. Aiming to investigate the influence of condition-based parameter to the final evaluation results, variation trends of the overall bridge evaluation results over condition-based parameter ($0 \le \alpha_s \le 1$) are plotted in Fig. 2. When condition-based parameter α_s equals to its smallest value (*i.e.*, $\alpha_s = 0$), the evaluation result is 71.81. According to Table 5, the grade of bridge is III and the recommended maintenance strategy is medium repair. As a result, whichever the value of condition-based parameter is, the recommended maintenance strategy cannot be in line with the actual situation. It is therefore concluded that the condition-based parameter has limitations in adjusting weight assignment.

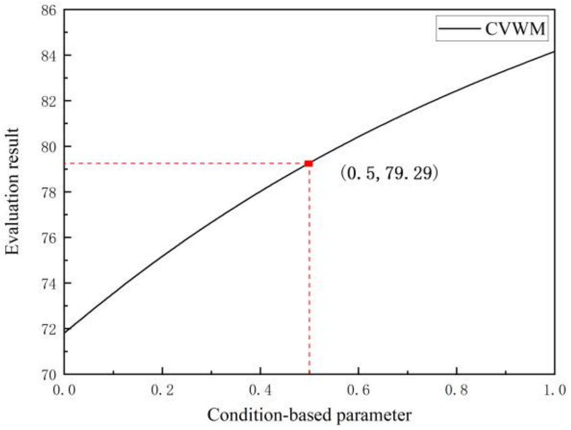


Fig. 2 Variation trends of evaluation results over the condition-based parameter

In addition, components of the superstructure are studied to investigate the variation law of weights over the condition value of indicators. It is assumed that all the components of the superstructure are in perfect condition except for the suspender. The condition of suspender is assumed to vary from perfect to unacceptable condition, *i.e.*, condition value of suspender decreases from 100 to 0. In this regard, variation trends of the suspender weight over its condition value are shown in Fig. 3, where the CVWM is employed and the condition-based parameter is 0.5. The weight of suspender increases slowly when the condition value varies from 100 to 20; when the condition value is smaller than 20, the weight increases significantly up to 0.67. The weight variation trend of the CVWM seems hardly capture the actual deterioration law of components. Based on engineering experience, the performance of components decays significantly when their grades reduce from III ([60, 80)) to IV ([40, 60)), which is supposed to deserve a substantial weight gain. For instance, the suspender in the aforementioned case study was damaged seriously, with the condition value 21.75. Whereas, the weight of suspender only increases from 0.17 to 0.297 in the CVWM. Considering the multi-layer evaluation model, the weight of suspender to the whole bridge structure further decays to 0.125. In fact, the damaged suspender behaves as the dominant factor to the performance of the whole bridge. The weight of suspender calculated from the CVWM seems mismatch its importance.

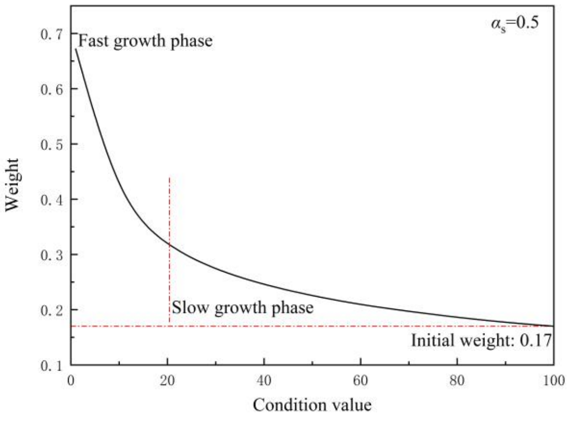


Fig. 3 Variation trends of the suspender weight over its condition value (α_s=0.5)

Based on the aforementioned discussions, the limitation of the CVWM in weight adjustment capability is owing to 1) the low initial weight and 2) the unsatisfactory weight variation trend. Xu et al. (2018) explored to construct a local variable weight model to make weight variation trend in line with the deterioration law. This paper intends to take advantages of age attributes of indicators to update the initial weight. The specific discussions are implemented in the following sections.

3. DEVELOPMENT OF AVWM

3.1 Definition of age-based variable weight

In addition to condition attributes of indicators for bridge assessment, indicators are also characterized by the service age. Based on the rationale that the probability of functional failure increases with the service age, it makes sense to pay more attention to those components servicing for long years by imposing more weights. Similar to the definition of condition-based variable weight, the concept of age-based variable weight is developed as follows:

Definition 2: Let $\mathrm{W}(\mathrm{T})$ be a set of *m*-dimensional age-based variable weight vector, denoted as $\mathrm{W}(\mathrm{T})=\left(\omega_1(\mathrm{T}),\omega_2(\mathrm{T}),\cdots,\omega_m(\mathrm{T})\right)$, which holds the following 3 properties:

(1) Normality: $\sum_{j=1}^{m}\omega_j(\mathrm{T})=1$;

(2) Continuity: $\omega_j(\mathrm{T})$ is continuous with each index service age; and

(3) Penalty: $\omega_j(\mathrm{T})$ is monotonically decreasing with respect to t_j.

where T is the set of *m*-dimensional epochs, $\mathrm{T}=(t_1,t_2,\cdots,t_m)$.

3.2 Construction of AVWM for bridge evaluation

The typical sum type balanced function is applied in the AVWM for bridge evaluation. The age-based variable weight of the *j*th indicator is expressed as

$$\omega_j(\mathrm{T})=\frac{\omega_j^0 t_j^{\alpha_t-1}}{\sum_{i=1}^{m}\omega_i^0 t_i^{\alpha_t-1}},\ \text{for } 0\le\alpha_t\le 1 \tag{7}$$

where α_t is the age-based parameter; and t_j is the age factor of the *j*th indicator, which is defined as

$$t_j = 1 - \frac{t_j^0}{T_j} \tag{8}$$

where t_j^0 is the service age, and T_j is the service life. If the actual service life of component is known, T_j equals to the actual service life, otherwise T_j equals to the designed service life.

Based on Eqs. (7) and (8), a small age factor is imposed on the component if the service age of the component approaches its service life, and it is expected to have a large variable weight based on the penalty in the definition. In other words, the closer the service age is to the service life, the more prominent the importance of the component is, which is represented by the increase of weight. In practical systems, the failure probability of a component usually increases with its operating age. The failure probability of a component at the end of service age is much higher than that at the installation instant. Therefore, it is necessary to focus on the performance of these components which approach their service lives to ensure a reliable operation of bridges. To this end, the variation trends of AVWM are kept consistent with the actual demands of bridge maintenance and management.

For the system layer within the evaluation framework, each indicator involves several components with various service lives. An equated service life is proposed for indicators in the system layer, which is

$$T_{sy} = \sum_{j=1}^{n} \omega_{j,co}(\mathrm{T}) \cdot T_{j,co} \tag{9}$$

where n is the number of components in the system; $\omega_{j,co}(\mathrm{T})$ is the age-based variable weight; and $T_{j,co}$ is the service life of the j^{th} component.

3.3 An illustrative example for AVWM

Components in the superstructure are used to depict the variation trends of index weights over the service life. According to Fig. 1, the superstructure consists of eight components, namely, stiffening girder, tower, bearing, tower saddle, main cable, cable band, suspender and anchor bolt, and the corresponding initial weights are

0.15, 0.20, 0.05, 0.04, 0.25, 0.04, 0.25, 0.04, 0.17 and 0.10, respectively.

Components in the superstructure are designed with various service lives. Based on JTG/T D65-05 (MOT, 2015b), the designed service lives of components in the superstructure are listed in Table 6.

Table 6 Designed service lives of components in the superstructure

Component	Stiffening girder	Tower	Bearing	Tower saddle	Main cable	Cable band	Suspender	Anchor bolt
Designed service life (year)	100	100	15	100	100	50	20	100

Based on Eqs. (7) and (8), variation trends of index weights within the designed service life of suspension bridges (100 years) are illustrated in Fig. 4. It is assumed that the exiting components are replaced once reaching their service lives.

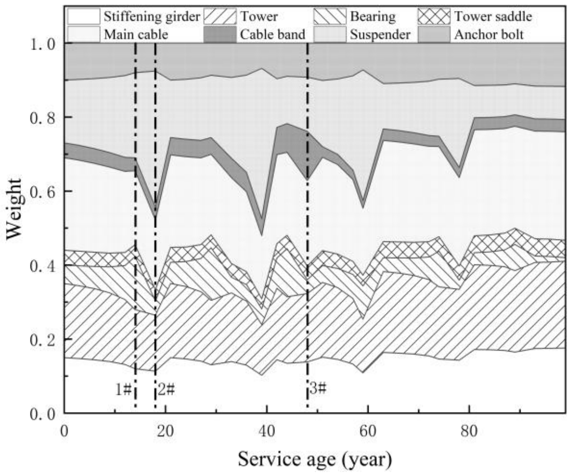


Fig. 4 Variation trends of component weights over the service life ($\alpha_t = 0.5$)

As shown in Fig. 4, the variation trends differ significantly between replaceable components and permanent ones. For replaceable components, their weights peak at the end of the designed service lives, while weights of the other components are contracted. For example, by the end of service life of the bearing (*i.e.*, time node 1# in Fig. 4), its weight approaches the peak, while weights of the other components are compressed. Similar variation laws can be observed for the suspender and cable band at time nodes 2# and 3#, respectively. In addition, the weights of replaceable components have an obvious periodicity within the designed service life of bridges, where the cycle lengths equal to their service lives. As for permanent components, their weights generally tend to increase steadily over the service life, whereas, the weights of permanent components will be compressed at the end of the service lives of replaceable components, especially at the early phase. In the later stage of operation, weights of the permanent main components are dominant in the bridge system. For instance, the weight of main cable increases gradually from 0.25 to 0.29 within the service life of bridges (100 years), however, in the early stage (*e.g.*, time node 1#), the weight of main cable decreases significantly from 0.25 to 0.20.

To sum up, weights of replaceable components and permanent components indicate different variation rules in the AVWM. Weights of replaceable components increase significantly when approaching the end of their service lives. Additionally, periodicity is observed within the service life of bridges (100 years), and the cycle lengths are their service lives. For permanent components, weights tend to increase gradually over the service life.

4 APPLICATIONS OF ACVWM

4.1 Construction of ACVWM

As discussed earlier, the limitations of CVWM in weight adjustment may result from the low initial weights. Thus, the AVWM is explored to gain initial index weights based on their service ages, which is calculated by using Eqs. (7) and (8). The CVWM is then incorporated with AVWM by replacing initial weights in Eq. (5) with age-based variable weight. In this regard, the expression of the ACVWM is as follows:

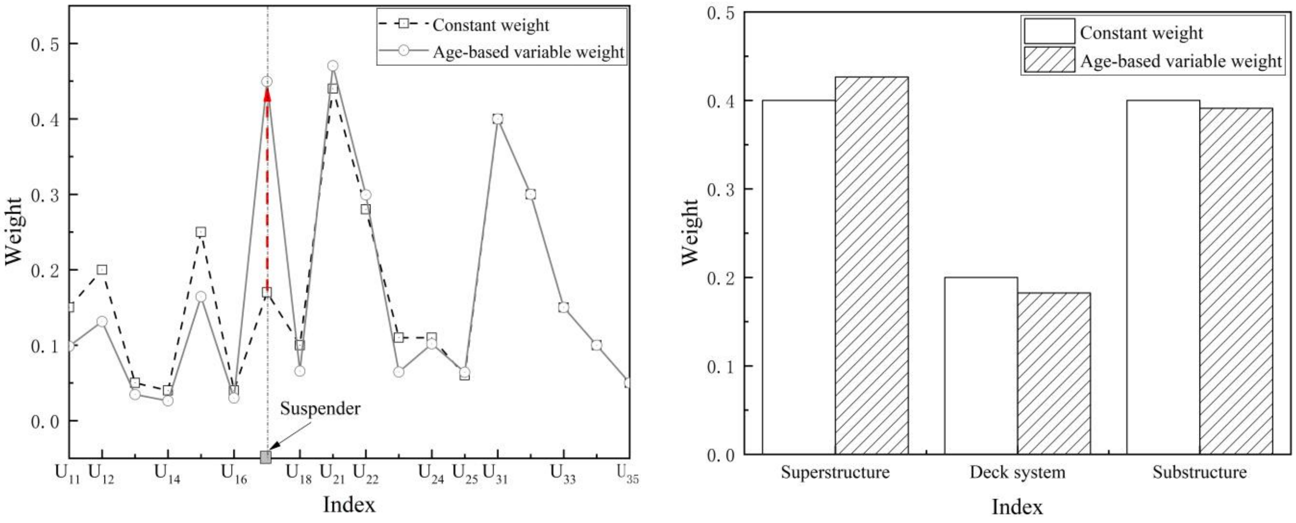
$$V\left(\mathrm{T},\mathrm{X}\right)=\sum_{j=1}^{m}\omega_j\left(\mathrm{T},\mathrm{X}\right)x_j=\sum_{j=1}^{m}\frac{\omega_j\left(\mathrm{T}\right)x_j^{\alpha_s}}{\sum_{k=1}^{m}\omega_k\left(\mathrm{T}\right)x_k^{\alpha_s-1}},\ \text{for } 0\le\alpha_s\le1 \tag{10}$$

where $\omega_j(\mathrm{T})=\dfrac{\omega_j^0 t_j^{\alpha_t-1}}{\sum_{i=1}^{m}\omega_i^0 t_i^{\alpha_t-1}}, \mathrm{for}\left(0\le\alpha_t\le 1\right)$.

Compared with the CVWM, the ACVWM has 2 parameters to adjust weight variation trends, which are condition- and age-based parameters. Combination of the AVWM and CVWM has potential to overcome the limitations of the CVWM in weight adjustment.

4.2 Case study

The aforementioned case study of the suspension bridge in Section 2 is employed to highlight the advantage of the ACVWM. The in-situ inspection information is listed in Table 2. In addition, the overall inspection activity was carried out in the 19th service year of the bridge (*i.e.*, $t_j^0=19$). According to Eq. (7), the age-dependent variable weights associated with the indicators are illustrated in Fig. 5. Since the service age of the bridge (19 years) approaches the service life of suspender (20 years), the weight of suspender (U_{17}) increases significantly when compared with other indexes.



(a) Age-based variable weight of components

(b) Age-based variable weight of systems

Fig. 5 Age-based variable weight of indexes ($\alpha_t=0.5$)

Subsequently, the ACVWM is applied based on the calculated age-based variable weights. The calculated parameters of the ACVWM are listed in Table 7.

Table 7 Calculation process of the ACVWM ($\alpha_s = 0$)

System	Component	$\omega_j(\mathrm{T})$	x	$\omega_j(\mathrm{T},\mathrm{X})$	Overall Evaluation result
U_1		**0.426**	**37.50**	**0.623**	54.75
	U_{11}	0.099	75	0.049	
	U_{12}	0.131	100	0.049	
	U_{13}	0.035	75	0.017	
	U_{14}	0.026	100	0.010	
	U_{15}	0.164	100	0.062	
	U_{16}	0.030	85.12	0.013	
	U_{17}	0.449	21.75	0.775	
	U_{18}	0.066	100	0.025	
U_2		**0.183**	**71.17**	**0.140**	
	U_{21}	0.470	61.74	0.542	
	U_{22}	0.299	72.5	0.294	
	U_{23}	0.065	100	0.046	
	U_{24}	0.102	100	0.072	
	U_{25}	0.064	100	0.046	
U_3		**0.391**	**90.35**	**0.237**	
	U_{31}	0.400	78.92	0.458	
	U_{32}	0.300	100	0.271	
	U_{33}	0.150	100	0.136	
	U_{34}	0.100	100	0.090	
	U_{35}	0.050	100	0.045	

The overall evaluation result of the studied bridge by using the ACVWM is 54.75 (Grade IV), corresponding to the category of overhaul according to Table 5. As previously mentioned, the recommended maintenance strategy (overhaul) from the ACVWM is in line with the reality. Compared with the CVWM, the ACVWM has the capability to gain initial weights based on the service age of bridges, which overcomes the shortcomings of the CVWM in weight adjustment.

In the maintenance and management activities of bridges, if the overall evaluation result of the bridge is low, it is critical to isolate the key component leading to the low overall score of bridges. Maintenance and reinforcement measures will then follow up to ensure the operational and structural safety. Variable weights reflect the priority level of each component within the specific evaluation result, which makes it feasible to determine the critical component. Taking the evaluation result in Table 7 as an example, the age- and condition-based variable weights are shown in Fig. 6, leading to an overall evaluation result of 54.75. As a result, the suspender with the heaviest weight is the most critical component for the current stage owing to the fact that the service age of the suspender is almost approaching to its service life and its condition is poor. Therefore, it is suggested to pay more attention to the suspender in the maintenance activity within the actual situation in this case study.

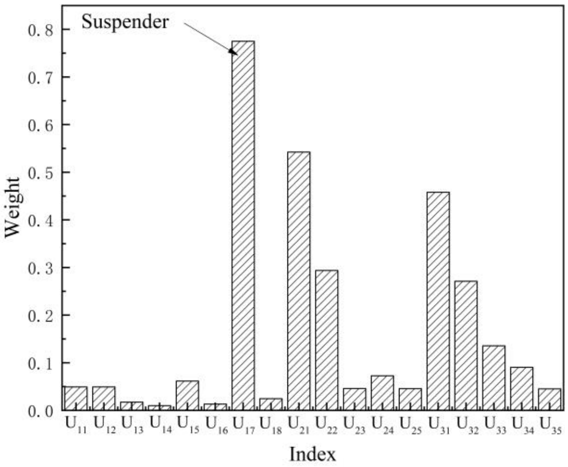


Fig. 6 Weight assignment of the ACVWM

Suspender replacement was adopted to improve the serviceability of the bridge. After replacement, the bridge was rated again for comparison. The evaluation results of the bridge before and after the replacement actions are listed in Table 8. The grade of the bridge is improved from Grade IV to II after replacing the suspender. It is evident that the condition of the bridge is restored to a satisfactory level after the overhaul measures.

Table 8 Evaluation results before and after replacement actions

Item	Before replacement	After replacement
Evaluation result of U_1	37.50	92.86
Evaluation result of U_2	71.17	71.17

Item	Before replacement	After replacement
Evaluation result of U_3	90.35	90.35
Overall evaluation result	54.75	86.85
Grade	IV	II
Maintenance strategy	Overhaul	Minor repair

5. CONCLUSIONS AND PROSPECTIONS

This paper developed an ACVWM to rate the performance of bridges, which overcomes the drawbacks of the CWM and CVWM in terms of weight adjustment. The following conclusions can be drawn from this study:

(1) Based on the definition of condition-based variable weight, the definition of age-based variable weights is developed. The AVWM is then constructed for bridge evaluation by considering the domain knowledge of bridge engineering. In detail, the typical sum type balanced function is used to formulate the AVWM, leading to an adaptive weight over the bridge service life.

(2) The variation law of the age-based variable weight is discussed for both replaceable and permanent components by using the index in the superstructure of suspension bridges. For replaceable components, the weight significantly increases at the end of the service life. In addition, the weight of replaceable component indicates periodicity within the whole designed service life, where the cycle length corresponds to its service life. For permanent components, the weight gradually increases with the service life.

(3) The case studies uncover the insufficient capabilities of the CWM and CVWM in adjusting index weights, resulting in unbalanced evaluation results and inappropriate recommended maintenance actions. The effectiveness of the ACVWM is validated by compared with the evaluation results of the CWM and CVWM. As a result, the evaluation result of the ACVWM is more in line with the actual situations compared with the CWM and CVWM. The advantages of the ACVWM lie in its capability to adjust the initial weights over the service age, which overcomes the drawbacks of the CVWM in low initial weights resulting in unsatisfactory weight assignment.

In this study, the service age is taken into account to modify the condition-based bridge performance evaluation in a general way. In the future, the factors of environments, required functions, and qualities of inspection and monitoring are expected to be involved in the evaluation method to make evaluation results more rational.

DATA AVAILABILITY

The data used to support the findings of this study are included within the article.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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