Delay-based Maintenance Cycle Prediction System for QR Codes on Outdoor Cultural Heritage Panels

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***Abstract*—This paper proposes a maintenance cycle prediction system for Quick Response (QR) codes used on outdoor cultural heritage information panels, where damage states are assessed by measuring the recognition delay, rather than simply classifying scan attempts as success or failure. The proposed system consists of a user application and a maintenance server; the server includes a damage recognition module, a data analysis and policy engine, and an administrator interface. The analysis and policy engine, which is at the core of the maintenance server, combines a delay-based damage index with regional environmental coefficients and material coefficients to derive replacement-interval policies. To evaluate the system, multiple QR codes were installed on Jeju coastal walkways, Gangwon fortress trails, and Jeju tourism information signs, and experiments were conducted over a six-month period. The results show that ordinary sticker-type QR codes require replacement after approximately three months, weather-resistant stickers after five to six months, while laminated information panels remain in normal condition throughout the six-month period. These findings demonstrate that recognition-delay-based damage assessment enables more effective and proactive maintenance operations and suggest that the proposed system can contribute to lifecycle management and the service quality of outdoor cultural heritage QR code infrastructures.**

***Keywords*—Quick Response (QR) code, cultural heritage, maintenance cycle, replacement priority, frequency of detection delay**

I. Introduction

As digital technologies are rapidly integrated into the operation of cultural heritage sites and other cultural venues, Quick Response (QR) codes have become a low-cost interface for delivering textual information, explanatory content, and multilingual services [1]. There is a growing number of cases in which QR codes are used instead of printed leaflets or traditional panels to provide dynamic content for outdoor heritage sites, walking trails, historical routes, and tourist information boards [2, 3]. In such outdoor environments, QR codes are mounted on various physical substrates such as plastic, metal, wood, and stickers so that they can remain in service for extended periods [4].

Previous studies in the cultural heritage and tourism domains have emphasized that QR codes can provide visitors with on-demand information, allow flexible updates of guide content, and support multilingual access and accessibility features [5, 6]. For example, in some heritage sites, QR codes are not used merely as static links but as entry points into a flexible infrastructure where target Uniform Resource Locators (URLs) are remapped via a server. In museums, environmental centers, and science centers, QR codes have been positively evaluated as tools that reduce the environmental burden of printed materials while still offering dynamic, real-time content delivery. However, most of these works focus on content delivery and user experience, and do not quantitatively model QR code deterioration to derive maintenance policies and replacement cycles [7].

Outdoor QR codes for cultural heritage information are engraved or printed on various materials such as plastic, metal, wood, and stickers to provide long-term service. Over time, however, fading, peeling, and scratches frequently occur, and damaged codes are often not replaced immediately. Such QR codes can lead to recognition failures when users attempt to scan them with smartphones, or to partial decoding that exceeds the error-correction capability and results in connection failures [8]. Existing guidelines for outdoor QR code maintenance recommend using weather-resistant materials, higher error-correction levels, dynamic QR codes, and regular inspections, but these remain at the level of practical advice; few data-driven models that determine replacement timing based on scan frequency or recognition delay have been proposed [9]. Consequently, on-site managers largely rely on empirical judgment to decide replacement timing, which can lead to both excessive replacement and insufficient maintenance.

To address these issues, this study proposes a recognition-delay-based maintenance cycle prediction system for outdoor cultural heritage QR codes. When a

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user scans a QR code with a smartphone, the application measures the recognition delay and reports this value to the maintenance server. The server analyzes the delay frequency relative to the total number of scans and, using regional environmental information and material properties, determines replacement priorities and appropriate maintenance intervals and then notifies the administrator. Whereas previous studies have typically judged damage based on scan success, the proposed approach treats recurring recognition delays as a signal of degradation: it measures the delay frequency and sends this information to the maintenance server for QR codes that are not visually destroyed but cause noticeable inconvenience to users. The proposed system consists of a user application and a maintenance server that comprises a damage recognition module, an analysis and policy engine, and an administrator interface, which together predict replacement cycles by combining recognition delay frequency, reported damage state, regional environmental stress, and material quality.

For performance evaluation, ten QR codes were installed at each of three locations—Jeju coastal walkway, Gangwon fortress trail, and Jeju tourism information boards—and experiments were conducted over six months. On ten randomly selected days per month, each site was visited once, and QR codes were scanned twice per visit (morning and afternoon) to assess damage status; five participants per site, i.e., fifteen in total, took part in the experiment. The results show that ordinary sticker-type QR codes on the Jeju coastal walkway exhibited a delay frequency exceeding 55% and a preservation damage index of about 0.7 after three months, indicating that replacement is required within one month after three months of installation. Weather-resistant stickers on the Gangwon fortress trail triggered replacement alerts in months five to six, while laminated information panels maintained a preservation damage index below 0.1 for six months, confirming that the proposed damage index and the replacement/inspection policy provide valid decision criteria across different environments and materials. These findings demonstrate that the proposed system and its analysis and policy engine are highly effective for deciding whether a QR code should be replaced. Furthermore, using recognition delay as the primary indicator of damage shows a high correlation with visual assessments and helps reduce maintenance costs. In this way, the proposed system can contribute to improving both the stability and efficiency of digital information infrastructures for cultural heritage sites.

The remainder of this paper is organized as follows. Section II reviews the use of QR codes in cultural heritage and tourism and surveys studies on physical and environmental stress, printing media and materials, and damage caused by user interaction. Section III describes the architecture of the proposed system and the associated data flows. Section IV presents the numerical damage model and experimental scenarios for outdoor QR codes. Section V reports the experimental results and performance evaluation. Finally, Section VI concludes the paper and discusses directions for future research.

II. Related Work

QR codes have become a key digital touchpoint for delivering information in domains such as commerce, tourism, transportation, and healthcare, and when deployed in cultural heritage sites, tourist attractions, and urban environments, outdoor exposure, repeated physical contact, and user interaction patterns can jointly degrade recognition performance [10]. Early studies emphasized that QR code readability is determined by technical factors such as sensor resolution, light reflection, and display distortion, and proposed recognition algorithms and preprocessing methods to cope with low resolution, glare, and geometric distortion. For example, Sirikongtham and Nimkoompai [11] proposed a GAN-based image restoration model with spectral normalization that reconstructs scratched, torn, or faded QR codes and significantly improves decoding success rates compared with baseline methods. Muallim *et al.* [12] introduced a lightweight deep-learning framework and synthetic dataset for restoring damaged barcodes and QR codes in logistics applications, demonstrating large gains in decoding ratios under realistic contrast loss, misalignment, and wear conditions. In parallel, practical guidelines in maintenance and asset-management domains recommend using durable materials, protecting QR labels from direct sunlight and harsh weather, and performing periodic inspections, but these recommendations remain qualitative and do not provide quantitative models for when a QR code should be repaired or replaced.

In the cultural heritage and tourism sectors, QR codes are used as interfaces for guide texts, explanatory content, and AR/VR services, and many studies have examined their impact on visitor engagement and educational outcomes [13, 14]. For example, in environmental education signage, the introduction of QR codes has been shown to increase user awareness and participation, while also revealing that visual placement and surrounding lighting have a significant impact on recognition success rates [15]. In tourism behavior, QR codes have further expanded into payment and environmental information services, where user satisfaction has been shown to depend directly on recognition success and the reliability of the information provided [16].

In outdoor cultural heritage environments, QR codes have been widely used as an interface for providing interpretive information and multilingual guidance to visitors, and their placement and operational design can strongly affect readability and user experience. For example, Yanis *et al.* [17] demonstrated that integrating QR code information boards with a web-based system in a geo-tourism village allows richer on-site interpretation, monitoring of visitor numbers at each tourism site, and dynamic updates of links, images, and videos without reprinting the QR code. Their work highlights how outdoor QR code deployment and web integration can support both tourism development and educational objectives. On heritage trails, Deri *et al.* [18] discussed sustainable tourist signage that combines physical markers with digital access, emphasizing how material selection and environmental exposure affect the long-term usability and

maintenance needs of outdoor signs. Their work focuses on choosing substrates and designs that can withstand weathering while minimizing replacement frequency and environmental impact. This perspective complements the present study, which concentrates on modeling degradation and recognition delay for QR codes installed on such signage; in particular, the environmental and material coefficients in our damage index can be seen as a simple way to incorporate durability and sustainability considerations into maintenance decisions. More recently, studies on QR code infrastructure for outdoor heritage have shown that QR codes are evolving beyond simple information delivery tools into digital guidance systems that also consider maintainability and relocation flexibility [19]. Compared with these prior studies, the present work differs in that it focuses not on content delivery, but on predicting maintenance timing based on recognition delay and degradation status.

Physical damage factors vary depending on the printing substrate and material of the QR code. Paper-based QR codes are affected by ink quality, paper absorbency, and the presence or absence of coating, which influence absorption, peeling, and water ingress, and can ultimately reduce black–and-white contrast and blur some modules, leading to recognition failures [20, 21]. Sticker- and label-type QR codes are highly dependent on adhesive quality and surface treatment; when the surface is rough or contaminated with oil and dust, adhesion weakens, damage starts at the edges, and progressively spreads toward the central modules, resulting in decoding errors [22]. Even when printed directly on hard surfaces such as thermoplastic plastics, metals, or glass, which are generally heat- and chemical-resistant, micro-roughening or paint loss on the surface can blur module boundaries and push the code beyond its error-correction capability [23].

Environmental stress is another critical factor that accelerates QR code degradation. Outdoor QR codes exposed to sunlight for long periods experience gradual ink fading due to UV radiation and heat, and as the faded area increases, the contrast between black and white modules decreases, lowering recognition sensitivity [24, 25]. When rain, soil, windborne dust, and sand cover the surface, the actual module layout and the pixel pattern in the captured image no longer match, which disrupts the geometric correction and normalization algorithms in recognition libraries and leads to scan failures. In coastal and salt-affected areas in particular, salt can penetrate onto stickers, altering the adhesive, while corrosion and swelling of metal or plastic substrates can distort or partly erase the QR pattern.

User interaction also directly influences the progression of QR code damage. QR codes placed on tourist and urban information boards are repeatedly touched or brushed by hands, clothing, and bags as users bring their phones close, which can scratch the surface or leave oils and moisture that blur black and white modules. Some studies have noted that when QR code signs are installed below eye level or close to walls or pillars, repeated touching by children and accompanying adults accelerates surface fading and loss of adhesion. In addition, behaviors such as pointing at specific modules with a finger or painting over parts of the code to highlight text can disrupt the structural symmetry of the QR pattern and increase the likelihood of recognition failure even when portions of the code remain intact.

Building on these damage factors, technical approaches have been proposed to restore or maintain QR code recognition performance. For example, studies using deep super-resolution convolutional neural networks to restore low-resolution, blurred, or severely distorted QR images have demonstrated that various super-resolution models can recover degraded modules and enable successful decoding by standard recognition libraries. Other work has applied Generative Adversarial Network (GAN)-based architectures to reconstruct module patterns in damaged QR codes, achieving recognition success rates of roughly 70–88% even for damage levels between 1% and 60% [26, 27]. These studies show that real-world QR code degradation arises from a combination of physical media, environmental, and imaging conditions, but they do not address long-term, large-scale deployments in cultural heritage and tourism contexts in terms of damage level classification, cumulative degradation modeling, or replacement cycle prediction.

Research on materials and products to improve QR code durability has also increased since the early 2020s. “Durable QR panels” that use metal or weather-resistant plastics with water-, humidity-, and UV-resistant coatings have been reported to exhibit significantly less fading, peeling, and adhesion loss than paper or ordinary stickers, thereby reducing maintenance costs in outdoor environments [28]. QR codes printed directly on metal surfaces or protected with lamination show enhanced resistance to physical damage and improved durability against contact, scratching, rain, and salt exposure. However, these studies primarily focus on comparing material performance and extending service life, and do not systematically address how outdoor cultural heritage QR codes should be designed and managed in environments where material, installation position, visitor characteristics, operational policies, and maintenance practices all interact. In other words, existing research tends to treat QR code recognition technology, material durability, image restoration, and user perception separately, and there is a lack of work that integrates the degradation of outdoor cultural heritage QR codes across time, environment, material, installation, usage patterns, and data-driven maintenance.

III. The Structure of Delay-based Maintenance Cycle Prediction System

This study proposes a maintenance cycle prediction system for outdoor cultural heritage QR codes that relies on visitor participation to scan codes and combines QR recognition delay time with reported damage state to determine replacement cycles and priorities. Instead of using a simple binary criterion of scan success or failure, the system adopts the elapsed time from the start of scanning to successful recognition as the primary quality indicator, thereby more sensitively reflecting usability

problems that users experience in practice even when visual damage appears mild.

The proposed system consists of a smart-device application that reads QR codes and sends damage-related information, and a maintenance server. The maintenance server, in turn, is composed of a damage recognition module, a damage analysis and policy engine, and an administrator interface. Fig. 1 shows the overall structure and operational flow of the recognition-delay-based maintenance cycle prediction system for outdoor cultural heritage QR codes. In Fig. 1, the QR code damage analysis application is used by visitors to scan QR code installed at outdoor heritage sites, while simultaneously measuring the time required for recognition. When the recognition time exceeds a preset threshold k s, the corresponding QR code is classified as being in a "delay occurred" state, and when recognition succeeds the QR content and the measured recognition time are transmitted to the maintenance server. The maintenance server redirects the QR code link to the content server to deliver the requested information. If the application cannot decode the QR code within a longer upper bound threshold of t s, the user may manually select the damage state and transmit this information to the server. The maintenance server then stores the QR information together with the recognition delay time and uses the damage recognition module to analyze the accumulated records of delay and QR code data. The maintenance server then uses the damage recognition module to analyze cumulative records of delay and QR code data, determines whether certain codes at specific locations are repeatedly delayed and how recognition speed changes with seasons or installation materials, and decides maintenance and replacement timing, which is then presented to the administrator through the interface.

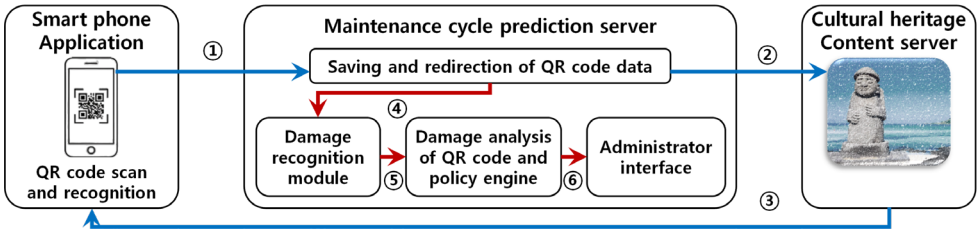


Fig. 1. System architecture for QR code damage-driven maintenance in outdoor cultural heritage panels.

The smartphone application used in this system can be implemented as a library that recognizes QR codes and sends data to the maintenance server. It measures the time from the moment the user temporarily pauses to scan until the moment the code is successfully recognized. When recognition is completed, the application transmits the content link, QR code identifier, GPS location, recognition delay time, and any user-selected damage state to the maintenance server, which then applies the QR damage recognition module and stores the data. The damage recognition module classifies states according to recognition delay as follows: when the QR code is recognized within k s, it is labeled as "no damage" (normal, damage rate below 50%); when recognition occurs after k s but within t s, it is labeled as "partially damaged" (damage rate 50% or higher); when recognition occurs only after t s, it is labeled as "severely damaged" (damage rate 80% or higher); and when the user explicitly reports damage, it is labeled as "unreadable." These classified states are stored in a QR code data table. Fig. 2 illustrates examples of QR code damage states.

Fig. 2(a) represents a QR code with no damage after creation; Fig. 2(b) shows a case where the center and lower-left areas are slightly damaged but the code is still recognized immediately, corresponding to a damage rate below 50%; Fig. 2(c) represents partial damage with more than 50% of critical modules affected in the upper-right and central-left regions; and Fig. 2(d) depicts a severely damaged, effectively unreadable state in which recognition fails in most attempts.

The damage analysis and policy engine then determines replacement priorities by aggregating regional environmental factors, material properties, exposure conditions, and historical recognition frequency. For example, QR codes installed in coastal areas of Jeju are strongly affected by sea breeze, salt, and UV radiation, whereas those in mountainous regions of Gangwon are more heavily influenced by freezing, snowfall, precipitation, and temperature fluctuations. This implies that even if two locations exhibit similar recognition delay histories, the resulting damage rates should be interpreted differently depending on the environment. Accordingly, the damage analysis and policy engine defines maintenance scenarios based on recognition delay frequency, region-specific correction values derived from environmental stress, and the material on which the QR code is printed and uses these scenarios to decide both the maintenance interval and whether a code should be replaced immediately. The resulting decisions are then communicated to the administrator through the interface.

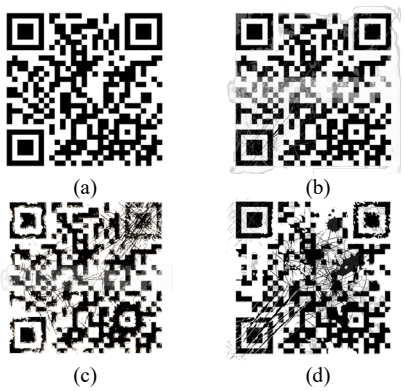


Fig. 2. Examples of QR code damage levels: (a) no damage, (b) damage rate 50% below, (c) partial damage between 50% and 80%, (d) severe damage of 80% over, unreadable.

IV. Maintenance Scenario and Damage Analysis Policy Engine

This section describes the numerical model of the damage analysis and policy engine, the damage index, and the replacement decision algorithm according to the maintenance scenarios for outdoor cultural heritage QR codes. Because environmental stress conditions vary widely across locations, this study focuses on three representative environments: Jeju coastal walkways, Gangwon fortress and mountain trails, and Jeju tourism information boards. The study areas were intentionally selected to represent different types of outdoor environmental stress conditions rather than being chosen arbitrarily. Jeju coastal walkways was selected as a representative coastal environment because QR codes installed there are exposed to strong salt, sea breeze, and ultraviolet radiation, all of which can accelerate fading and adhesion loss. Gangwon fortress and mountain trails were selected as a representative mountainous walking environment characterized by freeze0thaw cycles, precipitation, and temperature fluctuations, which may increase edge lifting, surface wear, and delayed recognition. In contrast, Jeju tourism information boards were selected as a relatively milder tourism-signage environment in which environmental stress is lower, thereby providing a comparative baseline for evaluating the effects of harsher outdoor conditions. Through this design, the study aimed to compare how different environmental stress conditions influence QR-code degradation patterns and recognition delay in real-field operation. The QR codes are not printed in a uniform way but are implemented using three types of materials and coatings: ordinary stickers, weather-resistant stickers, and laminated panels.

The damage index is calculated from recognition delay frequency as in Eq. (1).

$$H = \frac{T_d}{T} \tag{1}$$

In Eq. (1), H denotes the damage index, T_d is the number of scans whose recognition delay exceeds k s, and T is the total number of scans. In other words, the index represents the proportion of scans that are recognized slowly. For example, if 40 out of 100 scans have a delay of at least k s, then $H = 0.4$. In this case, scans with delay longer than t s as well as user-reported damage events are also counted in T_d.

Even for the same nominal damage index, environmental stress can differ by region. To reflect this, a region-corrected damage index is defined as in Eq. (2).

$$H_r = H \times E \tag{2}$$

In Eq. (2), H_r is the region-corrected damage index and E is the environmental coefficient. The coefficient E can be adjusted according to local characteristics; in this paper, we set $E = 1.3$ for Jeju coastal areas, $E = 1.1$ for Gangwon mountainous areas, and $E = 1.0$ for urban tourist sites. Thus, even if the observed damage level is the same, locations such as the Jeju coast, where salt, UV radiation, and wind greatly increase the likelihood of degradation, are assigned higher values.

The material on which the QR code is printed also affects degradation. Paper or ordinary sticker-based codes are relatively vulnerable to environmental stress and tend to deteriorate more quickly, whereas metal or laminated panels degrade more slowly. To incorporate these characteristics, the damage index is further adjusted as in Eq. (3).

$$H_m = H_r \times M \tag{3}$$

In Eq. (3), M is the material coefficient for the QR code substrate, and H_m is obtained by multiplying the region-corrected damage index by this material factor. Similar to E, the coefficient M can be tuned to reflect material properties; in this study, we use $M = 1.0$ for paper/ordinary stickers, $M = 0.8$ for weather-resistant stickers, and $M = 0.5$ for metal/laminated panels. This mapping implies that, even in the same environment, the use of higher-quality materials can mitigate the effective damage assessment. The coefficients E and M are heuristic correction factors used to reflect relative environmental stress and substrate durability rather than fixed physical constants. In this system, larger coefficient values are assigned to sites exposed to stronger environmental stress because accelerated degradation is more likely under harsher conditions such as sea salt, UV radiation, wind, freezing, or frequent precipitation. Accordingly, for the same observed recognition-delay pattern, a coastal site is interpreted as having a higher maintenance urgency than a milder urban site, while a more durable substrate such as a laminated panel receives a smaller correction than an ordinary sticker. In this way, the coefficients serve as practical adjustment factors that preserve the relative ranking of maintenance priority across different environments and materials. To check the robustness of these heuristic coefficients, a simple sensitivity analysis was conducted by varying the environmental and material coefficients by ±10–20% around their nominal values. The resulting damage indices and maintenance priority rankings changed only slightly in absolute magnitude, while the relative ordering of QR codes and environments remained stable. This suggests that the coefficients act as practical adjustment factors and that the proposed framework is not overly sensitive to small perturbations in E and M.

The damage analysis and policy engine of the maintenance server computes the base damage index H from the accumulated scan and delay counts in the database, applies the environmental coefficient E and material coefficient M to obtain the final corrected index H_m, and then determines the replacement policy according to the rule in Eq. (4).

$$R(H_m) = \begin{cases} Immediate\ replacement & if\ H_m \geq 0.8 \\ Replacement\ within\ 1M & if\ 0.5 \leq H_m < 0.8 \\ Inspection\ within\ 3M & if\ 0.3 \leq H_m < 0.5 \\ Normal\ maintenance & if\ H_m \leq 0.3 \end{cases} \tag{4}$$

Before applying the rule in Eq. (4), the engine first checks whether the damage recognition module has already flagged a critically damaged state. If the delay-based damage index H is 0.5 or higher, or if user-reported damage events exceed a preset threshold of r occurrences, the engine issues an immediate replacement recommendation via the administrator interface without further evaluation under Eq. (4).

Example maintenance scenarios illustrate how the replacement decision adapts to environmental stress and material properties. For QR codes implemented as ordinary stickers along the Jeju coastal walkway, sea breeze, salt, and strong UV radiation can rapidly accelerate ink fading and loss of adhesion. If the frequency of recognition delays of at least t s is 55 out of 100 scans, then $H = 55/100 = 0.55$, which meets the critical condition described above and leads to an immediate replacement recommendation prior to applying Eq. (4). If the delay frequency is instead 40 out of 100 scans, $H = 0.4$, and with $E = 1.3$ for Jeju and $M = 1.0$ for ordinary stickers, the corrected index becomes $H_m = 0.4 \times 1.3 \times 1.0 = 0.52$. According to Eq. (4), this value falls into the "replacement within 1 month" category, and the administrator is notified accordingly. For QR codes on the Gangwon fortress trail, winter freezing, snowfall, moisture, and temperature fluctuations often cause sticker edges to lift. Suppose weather-resistant stickers are used and 38 out of 100 scans exhibit recognition delay. With $E = 1.1$ for the region and $M = 0.8$ for the material, the corrected index is $H_m = (38/100) \times 1.1 \times 0.8 = 0.3344$. Since this value lies between 0.3 and 0.5, the rule in Eq. (4) classifies the code as requiring inspection within 3 months.

V. Experiments and Evaluation

This section evaluates the practical effectiveness of the QR-code recognition-delay-based damage assessment and replacement policy proposed in Sections III and IV by applying the system and numerical model to three outdoor environments: Jeju coastal walkways, Gangwon fortress trails, and Jeju tourism information boards. The experimental period spans six months, from October 2025 to March 2026. In each environment, ten QR codes were installed, and the proposed smartphone application was used to collect recognition delay times and user-reported damage states.

The experimental environments and measurement variables were defined as follows.

- Experimental environments

(1) Jeju coastal walkway: ordinary sticker-type QR codes in a harsh coastal environment with strong sea breeze, salt, and UV exposure.
(2) Gangwon fortress trail: weather-resistant sticker QR codes in an environment subject to freezing, snowfall, and heavy rain.
(3) Jeju tourism information boards: laminated QR panels in a mixed coastal and urban setting.

- Measurement variables

(1) Recognition delay time: elapsed time from the start of QR scanning to successful recognition.
(2) Delay frequency: proportion of scans with recognition delay ≥5 s.
(3) Damage reports: cases where the delay time ≥10 s or the user explicitly reports an unreadable state.

The study was designed as a field-based pilot to validate degradation and recognition-delay patterns under different outdoor conditions rather than as a large-scale generalization study. At each of the three experimental environments, 10 QR codes were installed, resulting in a total of 30 codes across all sites. Five participants were assigned to each environment, and they scanned the installed QR codes twice a day (morning and afternoon) on 10 randomly selected days per month over the six-month period. This design yielded repeated observations for each QR code, providing sufficient data to analyze month-to-month trends in recognition delay and to compute the proposed damage indices at the code and environment levels. And given this repeated-measurement design, the statistical analysis focuses on comparing relative degradation trends and index values across environments and materials, rather than on estimating population-level effect sizes for all possible QR code deployments.

In the experimental setup, the QR codes were measured under a standardized protocol designed to reduce unnecessary variation in recognition delay. To the extent possible, measurements were conducted at approximately the same time of day, and the scanning distance and viewing angle were kept consistent across all observation rounds. Each QR code was scanned repeatedly under the same procedure, and the recognition delay values from repeated scans were averaged to obtain the final value used in subsequent analysis. This procedure was adopted to improve comparability across sites and to reduce incidental variation unrelated to QR code degradation.

In Experimental Environment 1 (Jeju coastal walkway), the recognition delay frequency remained acceptable for the first two months but increased to more than 55% after three months. Visual inspection revealed that, at that point, eight out of ten QR codes exhibited fading and peeling over more than 50% of the code area. Table I summarizes the recognition delay frequency and the resulting preservation damage indices computed from the maintenance server data for months three and four at the Jeju coastal walkway. In Table I, the preservation damage indices at month three exceed 0.6 for all ten QR codes, which, when processed by the analysis and policy engine, triggers a "replacement within 1 month" recommendation according to the predefined rules.

By month four, the delay frequencies further increase, and many codes fail to be recognized at all. Some codes are still recognized with delay, which is likely because scans were performed on ten random days within the month, so successful recognitions tended to occur in the early part of the fourth month shortly after crossing the three-month threshold. Fig. 3 presents a statistical plot for the Jeju coastal walkway, showing the aggregated recognition delay frequency and preservation damage index over six months across the ten QR code locations.

TABLE I. SCAN DELAY INDEX H_M AFTER 3 AND 4 MONTHS OF EXPERIMENT ON JEJU COASTAL PROMENADE

QR Code	Total Scan	Delays 5 s over		H_m	
		3 months	4 months	3 months	4 months
1	100	55	86	0.715	1.118
2	100	58	89	0.754	1.157
3	100	59	81	0.767	1.053
4	100	48	78	0.624	1.014
5	100	53	88	0.689	1.144
6	100	47	76	0.611	0.988
7	100	61	87	0.793	1.131
8	100	59	83	0.767	1.079
9	100	48	81	0.624	1.053
10	100	65	88	0.845	1.144
Total	1000	553	837	0.719	1.088

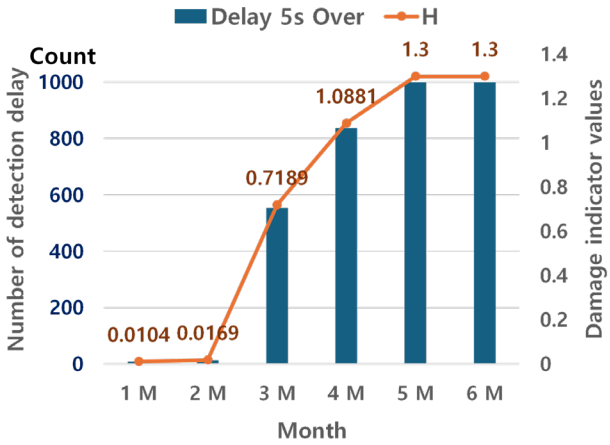


Fig. 3. Time series plots of recognition delay and index H_m for Jeju coastal walkway over six months.

In Fig. 3, it can be statistically confirmed that there are no significant issues with QR code recognition during the first two months, while the recognition delay frequency increases sharply from the third month and the codes become almost unreadable from the fourth month onward. In particular, the preservation damage index at month three is 0.719, which triggers a "replacement within 1 month" notification, and it is observed that more than 80% of the QR codes fail to be recognized after one month from that analysis date. This confirms that the decision made by the damage analysis and policy engine on the maintenance server is valid and consistent with the actual degradation behavior.

To provide visual documentation of the degradation process, Fig. 4 shows representative photographs of one QR code installed on the Jeju coastal walkway at three stages of the experiment. At installation in Fig. 4(a), the code surface is clean and the module pattern exhibits high contrast, and all test scans were recognized immediately without delay. After one month in Fig. 4(b), slight wear and minor discoloration appear on the surface, but the code remains visually intact and recognition still occurs without noticeable delay. By the third month in Fig. 4(c), however, substantial physical deterioration is visible, including smeared dark marks and a marked loss of contrast across a large portion of the modules; at this stage, many scans show significant recognition delay or complete failure. These representative images qualitatively support the observed relationship between increasing recognition delay and the progression of physical deterioration in the coastal environment.



(a) (b) (c)

Fig. 4. Photos of the status change of the installed QR code on the Jeju coastal walkway: (a) at installation (month 0), (b) after 1 month of outdoor exposure, (c) after 3 months of exposure.

In Experimental Environment 2 (Gangwon fortress trail), the recognition delay frequency rises to about 38% after three months, and edge lifting caused by freezing and snowfall is observed on more than 75% of the stickers. Table II summarizes the recognition delay frequency and preservation damage indices computed from the maintenance server data for months three and four at the Gangwon fortress trail.

In Table II, the average preservation damage index at month three is 0.335 across the ten QR codes, which corresponds to a "inspection within 3 months" decision when the analysis and policy engine rules are applied; at month four, the average index increases to 0.381, which still falls into the same "inspection within 3 months" category.

TABLE II. SCAN DELAY INDEX H_M AFTER 3 AND 4 MONTHS OF EXPERIMENT ON GANGWON FORTRESS TRAIL

QR Code	Total Scan	Delays 5 s over		H_m	
		3 months	4 months	3 months	4 months
1	100	33	44	0.294	0.387
2	100	41	53	0.361	0.466
3	100	40	56	0.352	0.493
4	100	36	50	0.317	0.440
5	100	39	53	0.343	0.466
6	100	43	58	0.378	0.510
7	100	40	59	0.352	0.519
8	100	34	49	0.299	0.431
9	100	33	51	0.290	0.449
10	100	42	55	0.370	0.484
Total	1000	381	528	0.335	0.465

However, by month six, the preservation damage index increases sharply, as illustrated in Fig. 5.

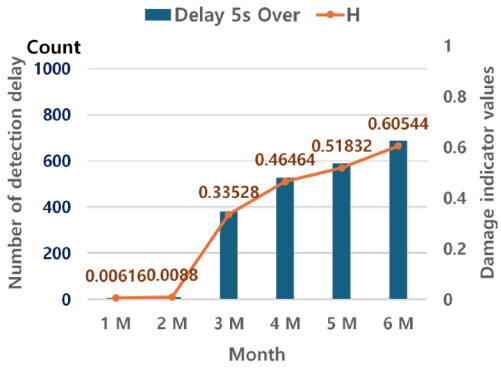


Fig. 5. Time series plots of recognition delay and index H_m for Gangwon fortress trail over six months.

In Fig. 5, QR code recognition is largely problem-free during months one and two, while in months three and four the recognition delay frequency begins to increase for some codes. The analysis and policy engine reports a "inspection within 3 months" alert starting from month three when the preservation damage index reaches 0.33528, and again at month four when the index rises to 0.46464. Thereafter, in month five the preservation damage index increases further to 0.51832, leading the engine to issue a "replacement within 1 month" recommendation, and in month six the rapid increase in recognition delay frequency results in another "replacement within 1 month" decision. These results indicate that, for the Gangwon fortress trail, the preservation damage index that incorporates recognition delay frequency, regional environmental stress, and material characteristics provides a reliable decision criterion for the maintenance server.

Finally, in Experimental Environment 3 (Jeju tourism information boards), the recognition delay frequency remains below 12% throughout the six-month period. Fig. 6 presents a statistical plot of the aggregated recognition delay frequency and preservation damage index over six months for the ten QR codes installed on the Jeju tourism information boards.

In this case, the tourism boards are located in an urban tourist area where environmental stress is relatively mild, and the laminated material results in minimal observable degradation. Over the six-month experimental period, the preservation damage index stays below 0.1, as shown in Fig. 6, so the analysis and policy engine consistently classifies the codes as "normal maintenance" and does not issue any replacement alerts. It should be noted, however, that laminated panels are relatively expensive compared to ordinary and weather-resistant stickers, making frequent QR code replacement less economical. The results therefore show that the proposed system recognizes QR code printed on laminated panels as stable and refrains from recommending replacement within the six-month window.

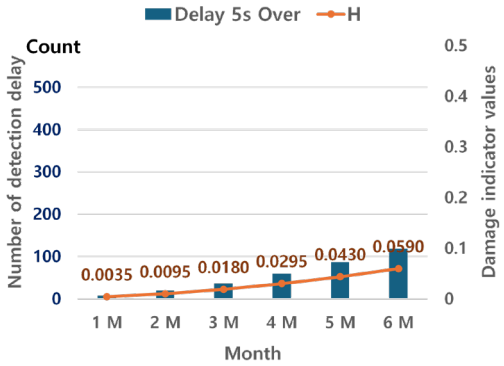


Fig. 6. Time series plots of recognition delay and index H_m for Jeju tourism information signs over six months.

Next, to clarify the practical value of the proposed method, Table III compares the proposed recognition-delay-based maintenance policy with two baseline strategies: a fixed 3-month replacement schedule and a visual inspection-based policy. The comparison is presented qualitatively in terms of early replacement count, missed deterioration cases, and maintenance efficiency. As shown in the table, the proposed method is expected to reduce unnecessary early replacement while maintaining timely intervention for deteriorated QR code, whereas the fixed replacement policy may lead to excessive replacement and the visual inspection-based policy may delay maintenance until damage becomes visually obvious. Therefore, the proposed framework provides a more balanced and adaptive maintenance strategy for outdoor QR code infrastructure.

TABLE III. QUALITATIVE COMPARISON OF MAINTENANCE POLICIES FOR OUTDOOR QR CODES

Policy	Decision Rule	Early Replacement Count	Missed Deterioration Cases	Maintenance Efficiency	Practical Interpretation
Proposed system	Replace based on recognition delay and corrected damage index	Low	Low	High	Adaptive to actual degradation and field conditions
Fixed 3-month replacement	Replace all QR code every 3 months	High	Low to medium	Moderate to low	Simple, but may cause unnecessary early replacement
Visual inspection-based	Replace only when damage is visually obvios	Low	High	Moderate	Low cost, but may delay intervention

Finally, to quantitatively assess the relationship between visual degradation and the proposed damage index, correlation analyses were performed on the aggregated code-month pairs. The visual degradation level was rated on an ordinal scale (0: no visible damage, 1: slight damage, 2: moderate damage, 3: severe damage/unreadable) based on field photographs and on-site inspection, while the damage index was computed from the proportion of scanes exceeding the delay threshold. This resulted in N paired observations (D_i, H_i), where D_i denotes the visual degradation score and H_i the damage index for the i-th QR code-month combination.

For each QR code in each month, we computed the damage index from all scans in that month and assigned a single visual degradation score based on field inspection. This resulted in 10 codes × 6 months = 60 paired observations per environment, and 180 observations in total across the three environments. The correlation analyses were performed on these aggregated code-month pairs, rather than on individual scans, in order to avoid inflating the sample size due to repeated measurements of the same code.

As summarized in Table IV, when all environments were combined, the visual degradation level and the damage index exhibited a strong positive association (Pearson $r = 0.73$, Spearman $r_s = 0.77$, both $p < 0.001$, $N = 180$). This indicates that codes rated as more severely degraded visually tend to have consistently higher values of the recognition-delay-based index. At the individual environment level, the spearman correlation remained positive and statistically significant in all three cases, but with different magnitudes that reflect the local environmental stress conditions. For the Jeju coastal walkway, the correlation was very strong ($r_s = 0.82$, $p < 0.001$, $N = 60$), which is consistent with the harsh coastal environment where salt spray, strong wind, and intense UV exposure accelerate fading, peeling, and surface contamination; in this setting, visual deterioration and recognition delay progress almost in lockstep. For the Gangwon fortress trail, the correlation was moderately to strongly positive ($r_s == 0.68$, $p < 0.01$, $N = 60$), reflecting a mountainous walking environment where freeze-thaw cycles, precipitation, and temperature fluctuations cause gradual edge lifting and material fatigue, leading to a clear but somewhat slower coupling between visual damage and recognition delay. In contrast, for the Jeju tourism information boards, the correlation was moderate ($r_s == 0.46$, $p < 0.05$, $N = 60$), which can be explained by the relatively mild environmental stress and the use of more durable panel materials; in this environment, visual damage accumulates slowly and the damage index shows smaller variation, but the positive and significant correlation still indicates that the index responds to the onset of degradation.

TABLE IV. CORRELATION BETWEEN VISUAL DEGRADATION LEVEL AND DAMAGE INDEX

Analysis Scope	Correlation Type	Correlation Coefficient	*p*-Value	N
All combined	Pearson	$r = 0.73$	$p < 0.001$	180
All Combined	Spearman	$r_s = 0.77$	$p < 0.001$	180
Jeju coastal walkway	Spearman	$r_s = 0.82$	$p < 0.001$	60
Gangwon fortress trail	Spearman	$r_s = 0.68$	$p < 0.01$	60
Jeju tourism info. boards	Spearman	$r_s = 0.46$	$p < 0.05$	60

VI. CONCLUSION AND FUTURE WORK

This study proposed a system that evaluates the degradation state of QR codes installed at outdoor cultural heritage sites using recognition delay time as a primary indicator, rather than relying solely on a binary scan success/failure criterion, and designed a maintenance framework that quantitatively determines replacement cycles and priorities based on this metric. The numerical model introduced in Section IV combines a delay-based damage index H, a regional environmental correction coefficient E, and a material correction coefficient M to derive interval-based maintenance policies—immediate replacement, replacement within 1 month, inspection within 3 months, and normal maintenance—that are intuitive for administrators to apply in real operations. The experiments and evaluations in Section V, conducted across three scenarios (Jeju coastal walkway, Gangwon fortress/trails, and Jeju tourism information boards), confirmed that damage assessment based on recognition delay time correlates strongly with visually observed degradation and enables more effective and proactive maintenance activities.

Given that QR codes have become a key digital touchpoint for cultural heritage interpretation and tourism guidance, this work is significant in that it moves beyond mere content delivery and proposes an integrated approach to managing the lifecycle and service quality of the underlying information infrastructure. Because cultural heritage QR codes simultaneously function as physical markers and digital entry points, a maintenance system that jointly considers recognition delay, physical degradation, environmental stress, material properties, and user behavior can enhance the robustness of digital transformation projects in this domain. At the same time, the present study has several limitations. Recognition delay can also be affected by non-degradation factors, including lighting, viewing angle, scanning distance, camera resolution, device performance, and network conditions, and the field setting did not allow complete separation of these confounding variables from QR code degradation despite a standardized measurement protocol. In addition, the sample size and the number of study sites are limited, as the work was designed as a field-based pilot with 10 QR codes per environment and three environments in total, so the findings should be interpreted as evidence of relative patterns and feasibility rather than as fully generalizable estimates.

Future research will therefore focus on extending the proposed method for broader applicability by quantitatively refining environmental and material coefficients under diverse stress conditions and by integrating image-based automatic damage detection algorithms, with the aim of evolving toward large-scale management systems for QR code infrastructures in cultural heritage and urban environments. Most users typically scan QR codes with the native camera application already installed on their smartphones rather than with a dedicated application, so another important direction is to remove the dependency on dedicated testers and a custom application by exploring browser-based timing, server-side redirect logging, or other lightweight-web-mediated approaches that do not require separate installation. A promising extension is to define

damage thresholds in terms of relative changes in recognition time rather than relying solely on the current linear formulation with heuristic coefficients, for example by classifying degradation levels based on how much the average recognition time increases relative to an initial baseline for each QR code, with the corresponding thresholds calibrated from empirical data. By pursuing these directions, future work can further generalize the proposed framework and contribute to more robust and scalable maintenance policies for outdoor cultural heritage QR code infrastructures.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

M.C. conceived the study, designed the methodology, implemented the algorithm, and led the experiments. J.P. assisted in developing the application for the experiments, participated in data collection, and performed the analysis of the experimental results. All authors have read and approved the final version of the manuscript.

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