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A FIELD STUDY ON THE APPLICABILITY OF DIGITAL-BASED RISK INSPECTION APPROACHES IN HISTORICAL AND MONUMENTAL STRUCTURES

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ABSTRACT

This study aims to examine the impact of digital risk inspection processes on conservation practices in historical and monumental structures by drawing on the experiences of domain experts. The research evaluates the implementation processes, technical advantages, operational limitations, and professional implications of HBIM (Historic Building Information Modeling), digital twin, laser scanning (TLS), photogrammetry, and sensor-based monitoring systems for use in cultural heritage conservation. The study group, designed within the framework of Interpretative Phenomenological Analysis (IPA), consists of 20 experts working in Istanbul in the fields of cultural heritage conservation, restoration, digital modeling, structural inspection, and risk management. Data were collected through semi-structured face-to-face interviews and analyzed using thematic analysis. The research findings indicate that digital technologies significantly contribute to making structural risks visible in cultural heritage sites, strengthening data-driven decision-making processes, and developing a preventive conservation approach. However, issues such as software incompatibility, data density, shortage of technical experts, and limited field applicability were found to impose significant operational limitations on digital transformation processes. The findings also reveal that experts view digitalization not merely as a technical transformation, but as a multidimensional field of change that reshapes professional roles, institutional structures, training processes, and ethical decision-making mechanisms. While participants believe that digital twin and AI-assisted systems will become more prevalent in conservation processes in the future, they emphasize that human expertise will continue to be decisive in terms of historical interpretation, cultural context, and intervention ethics. These results demonstrate that the sustainable implementation of digital conservation technologies requires not only technical infrastructure but also interdisciplinary collaboration, data standardization, institutional transformation, and development of hybrid expertise models. In this respect, the study offers a holistic perspective on the digitally based risk-inspection literature by centering practitioners' experiences.

Keywords: Cultural Heritage, Digital Risk Inspection, HBIM, Digital Twin, Preventive Conservation

INTRODUCTION

Cultural heritage sites are irreplaceable assets that represent the will and achievements of human history and transmit the identities and values of societies to future generations(Mekonnen & Tewodros, 2022).According to UNESCO, these sites encompass places of exceptional universal cultural, historical, and scientific value, including archaeological sites, historic monuments, urban landscapes, and industrial heritage(Wang et al., 2022).These sites are regarded not merely as physical structures, but as carriers of collective memory, social belonging, and cultural continuity(ICOMOS, 2015).The protection of cultural heritage is directly linked to sustainable development goals and is being reconsidered particularly within the frameworks of resilient cities, cultural sustainability, and societal resilience(UNESCO, 2021).However, these valuable structures are today under the pressure of natural disasters such as climate change, earthquakes, and floods, as well as anthropogenic threats including rapid urbanization, neglect, and armed conflict(Aktürk & Hauser, 2021).Such threats carry the risk of causing irreparable losses by compromising the material integrity and structural stability of historic buildings(Aktürk & Hauser, 2021; Raafat et al., 2026).

Traditional conservation approaches generally focus on curative methods that intervene after damage has already occurred, which typically results in costly and ineffective restoration processes due to delayed response(Matulionis & Freitag, 1991).In contemporary heritage management, "preventive conservation" strategies aimed at minimizing risks before damage occurs have come to the fore(Masciotta et al., 2021).Risk management is a systematic cycle consisting of the stages of risk identification, analysis, evaluation, and treatment(ISO 31000, 2018).In this process, digital-based approaches offer critical solutions for documenting the current condition of structures with high precision and monitoring potential deterioration through quantitative data(Salah et al., 2025; Chaves et al., 2024).In recent years, the "resilience-based conservation" approach has been aimed not only at protecting cultural heritage sites, but also at increasing their adaptive capacity against disasters and environmental changes(Sesana et al., 2021).When integrated with digital monitoring systems, this approach enables the early detection of risks and the proactive planning of maintenance processes.

Digital transformation has paved the way for data-driven and automation-based processes in cultural heritage conservation, as it has in the construction sector(Koparan, 2025).Historic Building Information Modeling(HBIM),which emerged from the adaptation of Building Information Modeling(BIM)technology to historic structures, represents structural elements not only geometrically but as a dynamic ecosystem that includes historical, material, and deterioration data(Murphy et al., 2009).Scan-to-BIM methodologies such as laser scanning(TLS)and photogrammetry used in HBIM processes enable the creation of "Digital Twin" models(Rocha et al., 2020).These models are optimized using standards such as Level of Detail(LOD),Level of Information(LOI),and Level of Accuracy(LOA)to facilitate risk-based decision support processes(Salah et al., 2025).Furthermore, the integration of Internet of Things(IoT)-based sensor systems with HBIM platforms enables the real-time monitoring of parameters such as temperature, humidity, vibration, and structural deformation(Angjeliu et al., 2020).Thus, micro-level changes occurring in historic structures can be detected at an early stage, and maintenance and intervention processes can be managed in a data-driven manner.

In the risk inspection of monumental structures, GIS-based risk maps are highly effective in determining the spatial distribution of environmental hazards and prioritizing restoration budgets(Ortiz et al., 2014).Moreover, the use of hybrid methods such as the Analytic Hierarchy Process(AHP)and SWOT analysis for weighting risk factors adds objectivity to inspection processes(Dammag et al., 2024).As exemplified by the Karatay Madrasa, scoring systems developed within the framework of standards such as the RE-ORG methodology and UNI EN 16096 provide a scientific basis for diagnosing the current condition of structures and determining the urgency of intervention(Bahtiyar & Dişli, 2022).However, data interoperability, lack of standards, and interdisciplinary coordination problems remain among the significant limitations in digital risk assessment processes(Bruno & Roncella, 2019).Data loss between different software platforms, and, in particular, the varying technical proficiencies of expert users hinder the sustainability of digital conservation processes.

A review of the literature reveals that the majority of studies on digital-based risk inspection present technical workflows focused on a specific digital tool or a particular historic building case study (Rocha et al., 2020; Chaves et al., 2024). Existing research generally focuses on the performance of laser scanning, photogrammetry, or specific software, while approaches concerning the practical applicability of these tools in complex historic fabric and user experience remain limited (Salah et al., 2025; Chaves et al., 2024). In particular, there is a very small number of studies examining the experiences of experts who use these digital models and inspection tools, the operational challenges they encounter, and the actual effectiveness of these models in decision-making processes (Rocha et al., 2020; Chaves et al., 2024). Chaves et al. (2024) emphasize that a repeatable, standardized, and user-friendly workflow to be made available to practitioners is still lacking. In addition, a significant portion of existing studies adopts a technology-centered approach, while insufficiently accounting for experiential differences among conservation experts, restorers, architects, and field practitioners. Yet the success of digital systems is directly related not only to technical accuracy, but also to user acceptance, ease of application, and the level of institutional adaptation (Marzouk & Othman, 2020). This study aims to fill this gap in the literature by addressing the applicability of digital risk-inspection approaches in historic and monumental structures from a holistic perspective. Within the scope of this research, not only theoretical models but also the views and experiences of the experts who use these models will be examined, and the role of digital transformation in conservation practice will be assessed. In this respect, the study aims to make an important contribution to the literature by going beyond technical methodologies and centering practitioners' perspectives.

2. METHOD

2.1. Research Design

This research was designed as a qualitative study using Interpretative Phenomenological Analysis (IPA), with the aim of examining how digitally based risk-inspection processes in historic and monumental structures are experienced and made meaningful by experts. IPA is an interpretive method that aims to investigate how individuals interpret their lived experiences of a particular phenomenon and the meanings they attribute to those experiences (Smith et al., 2021). The primary reason for choosing the IPA approach in this research is to reveal not only experts' technical experiences with digital risk inspection tools but also how they evaluate, make sense of, and integrate these processes into their professional practices. In IPA studies, it is important that the participant group shares a common experience around a particular phenomenon (Smith et al., 2021). Accordingly, the shared experiential domain of all experts in the study group is their active involvement in digitally based risk inspection processes in historic and monumental structures. At the same time, the inclusion of participants from different fields of expertise contributed to the interpretation of this experience from diverse professional perspectives. In this context, the study's core phenomenon is the experiential dimension of applying digital risk-inspection systems in cultural heritage structures. The research employed semi-structured interviews as the data collection method. Semi-structured interviews provide the researcher with the opportunity to collect data within a specific theoretical framework while also allowing participants to elaborate on their experiences in detail (Kallio et al., 2016). The primary reason for choosing this method is to uncover not only the technical dimensions of digital conservation practices but also multidimensional elements, such as user experience, decision-making processes, operational problems, and interdisciplinary coordination. Throughout the research process, ethical research principles were adhered to; informed consent for voluntary participation was obtained from participants, the purpose of the research was explained prior to the interviews, and participants were informed that the collected data would be used solely for scientific purposes. In addition, participants' identities were anonymized and all data were protected in accordance with the principle of confidentiality(American Psychological Association [APA], 2020).

2.2. Participants

The study group comprises 20 experts working in Istanbul in the fields of cultural heritage conservation, restoration, digital modeling, structural inspection, and risk management. The primary reason for selecting Istanbul as the study area is the city's multi-layered historic fabric, its dense cultural heritage inventory, and its hosting of major restoration projects, in which digital conservation practices are widely implemented. The presence of numerous monumental structures from the Byzantine, Ottoman, and Republican periods within a single city enables evaluation of digitally based risk-inspection practices across different building types. Participants were identified using criterion sampling, a purposive sampling method. In the criterion sampling approach, the researcher includes individuals who meet specific experience and expertise criteria(Patton, 2014).Accordingly, the key criteria for inclusion were having worked on cultural heritage projects, having experience with digital inspection technologies (HBIM, GIS, TLS, photogrammetry, etc.), and having at least five years of professional experience.

The primary reason for recruiting 20 participants is to achieve data saturation in qualitative research. Data saturation refers to the point at which data obtained from new interviews no longer meaningfully expands existing themes (Guest et al., 2006). The literature indicates that 5 to 25 participants may be sufficient for phenomenological studies (Creswell & Poth, 2016). Additionally, Hennink and Kaiser (2022) note that meaning saturation and thematic repetition can be achieved in most qualitative studies between approximately 16 and 24 participants. In this context, interviews with 20 experts were deemed sufficient to comprehensively address the study's research questions.

Attention was paid to ensuring interdisciplinary diversity within the participant group: professionals from various fields of expertise, including architecture, civil engineering, restoration, art history, geomatics engineering, and cultural heritage management, were included in the study. The aim was to evaluate digitally based risk inspection processes from different professional perspectives.

Table 1: Demographic and Professional Information of Participants

Variable	Group	Frequency (n)
Field of Expertise	Civil Engineering	4
	Architecture / Restoration Architecture	4
	Restorer / Restoration Specialist	4
	Geomatics Engineering	3
	Art History	2
	Urban Planning	2
Professional Experience	5–9 years	7
	10–14 years	9
	15 years and above	4
Area of Work	Restoration and conservation practices	6
	Structural risk and seismic analysis	4
	Cultural heritage management and analysis	2
	Mapping, spatial analysis and digital documentation	5
	Building maintenance, monitoring and digital modeling	3
Digital Technology Experience	HBIM	6
	GIS	5
	TLS	4
	Photogrammetry	4
	BIM	3
	Digital Twin	3

An examination of the participant group revealed that 20 experts from different disciplines were included in the study. Of the participants, 4 are civil engineers, 4 are architects/restoration architects, 4 are restorers/restoration specialists, 3 are geomatics engineers, 2 are art historians, and 2 are urban planners. In terms of professional experience, 7 participants have 5–9 years of experience, 9 have 10–14 years, and 4 have 15 or more years. Regarding areas of work, 6 participants are active in restoration and conservation practices; 5 in mapping, spatial analysis, and digital documentation; 4 in structural risk and seismic analysis; 3 in building maintenance, monitoring, and digital modeling; and 2 in cultural heritage management and analysis. In terms of digital technology experience, 6 participants have experience with HBIM, 5 with GIS, 4 with TLS, 4 with photogrammetry, 3 with BIM, and 3 with digital twin technologies. This distribution demonstrates that the research group possesses multidisciplinary, technology-oriented expertise in the conservation, risk management, and digital monitoring of historic and monumental structures.

2.3. Data Collection and Procedure

Research data were obtained through semi-structured interviews. In preparation for the interview form, the literature on digital cultural heritage management, risk inspection, HBIM applications, and digital transformation processes in historic buildings was examined in detail, and a pool of questions was developed in line with this theoretical framework. The interview questions were designed in an open-ended format, capable of eliciting detailed information about participants' technical experiences, operational problems encountered during implementation, interdisciplinary coordination experiences, and effects of digital systems on decision-making processes. To ensure the content validity of the questionnaire, the opinions of two academics specializing in cultural heritage management and qualitative research were sought, and necessary revisions were made to the questionnaire based on their feedback.

Experts who agreed to participate in the study were provided prior to the interviews with detailed information regarding the purpose and scope of the research, the data usage process, and the ethical principles. After obtaining informed consent for voluntary participation, interviews were conducted face-to-face at dates and times convenient for the participants. All interviews were conducted by the researcher. The interviewers have experience in qualitative research methods, semi-structured interview techniques, and digital conservation practices in the field of cultural heritage. Throughout the interview process, the researcher avoided directive language and allowed participants to express their experiences in detail from their own perspectives.

The primary reason for choosing the semi-structured interview approach in this study is that it allows in-depth of participants' experiences with digitally based risk inspection processes. Semi-structured interviews provide the researcher with the ability to collect data within specific themes while also allowing participants to share experiences that may be unexpected yet relevant to the research (DeJonckheere & Vaughn, 2019). This approach is noted to be particularly effective in practice-oriented qualitative research for revealing participant experiences in a multidimensional manner (Jamshed, 2014).

Interviews were conducted in Istanbul at participants' work offices, restoration sites, or university settings. Each interview lasted approximately 40–65 minutes and was audio-recorded with the consent of the participants. During the interviews, participants were asked about the use of digital risk inspection tools, their technical advantages and limitations, users' experiences, data management processes, interdisciplinary coordination problems, and their effects on decision-making processes. The collected audio recordings were transcribed into written text by the researcher, and accuracy checks were performed prior to analysis. In order to enhance the accuracy of the data, interview transcripts were sent back to participants and member checking was applied (Lincoln & Guba, 1985). To protect participants' confidentiality, each participant was assigned a code (P1, P2, P3, ...) during the interview process.

2.4. Data Analysis

The data obtained in the study were analyzed using Interpretative Phenomenological Analysis(IPA). IPA is an interpretive and idiographic analytical approach focused on examining how individuals make sense of a particular experience (Smith et al., 2021). In this approach, the researcher not only describes participants' experiences but also interprets the meanings that participants attribute to their experiences. The analysis process was carried out in accordance with the stages proposed by Smith et al. (2021). In the first stage, interview recordings were read repeatedly to establish familiarity with the data. Detailed descriptive, linguistic, and conceptual notes were then taken for each interview. In the next stage, experiential themes emerging from participants' statements were identified, and the relationships between themes were examined. Subsequently, themes across all participants were compared, and common patterns and divergent experiences were interpreted. Throughout the analysis, each participant was treated as a separate case, and care was taken to preserve the uniqueness of participants' experiences in line with IPA's idiographic approach. In order to enhance the consistency of the researchers' interpretations, researchers' memos were kept throughout the analysis process, and care was taken to ensure that interpretations were supported by direct participant statements.

2.5. Reliability and Validity

To enhance the credibility and scientific consistency of the research, the reliability and validity criteria proposed by Lincoln and Guba (1985) were employed. In this context, the principles of credibility, transferability, dependability, and confirmability were considered. To enhance credibility, techniques such as prolonged engagement, member checking, and expert review were employed. The accuracy of data transfer was ensured through participants' review of interview transcripts. The involvement of two independent researchers in the data analysis process also increased coding reliability. To ensure transferability, the research process, participant characteristics, data collection method, and analysis stages were described in detail, thereby providing methodological transparency for researchers wishing to conduct similar studies in comparable contexts. To ensure dependability, all stages of the research were systematically recorded, and an auditable research trail was established. To ensure confirmability, care was taken to support researcher interpretations with direct participant statements and to report data sources, coding processes, and stages of theme development in detail. Furthermore, in keeping with the interpretive nature of the IPA approach, researcher reflexivity was given importance; reflexive memos were kept throughout the analysis process to enable researchers to evaluate their interpretive positioning within the process (Smith et al., 2021).

3. RESULTS

Interpretive phenomenological analysis revealed that participants' experiences were structured around three main themes and associated sub-themes. The themes reveal how experts experience digitally based risk inspection processes, how they make sense of these processes, and what technical, institutional, and professional dynamics they encounter in their application practices. The main themes and sub-themes obtained are presented in Table 2.

Table 2. Main Themes and Sub-themes Obtained as a Result of Interpretative Phenomenological Analysis

Main Theme	Sub-themes
The Transformative Role of Digital Technologies in Conservation Practices	• Making invisible structural risks visible • Data-driven decision-making processes • Transition from traditional inspection to digital monitoring
Technical and Operational Challenges in Digital Risk Inspection Processes	• Software incompatibility • Data density and data management problems • Shortage of technical experts • Field applicability issues
Professional Perceptions and Expectations Regarding the Future of Digitalization	• Digital twin and artificial intelligence expectations • The role of human expertise • Need for training and institutional transformation • The future conservation paradigm

3.1. The Transformative Role of Digital Technologies in Conservation Practices

This theme focuses on how digital technologies are transforming traditional modes of practice in cultural heritage conservation. An examination of participant narratives reveals that HBIM, GIS, TLS, photogrammetry, and digital twin applications are not perceived merely as technical tools but as part of an epistemological transformation reshaping the understanding of conservation. Experts stated that digital systems significantly contribute by making risks to historic structures visible, strengthening data-driven decision-making, and continually reorganizing conservation interventions. At the same time, participants emphasized that digital technologies cannot fully replace traditional field experience.

3.1.1. Making Invisible Structural Risks Visible

The majority of participants perceived digital scanning and modeling technologies as enhancing the "readability" of historic structures. Laser scanning and photogrammetry applications, which, in particular make micro-level changes on building surfaces visible, were described by experts as a different experience from traditional observation-based inspection. Participants stated that structural problems, which were previously detected largely through field experience and intuitive assessment, can now be tracked with measurable data. P4's statement that "*when we transfer the scanning data to the model, we can see deformations that were previously missed much more clearly*" points to the capacity of digital systems to render visible risks that are difficult to perceive in complex historic structures. Sharing a similar perspective, P10 emphasized that tracking small movements in domes and load-bearing systems through traditional methods is extremely difficult, saying, "*It is very hard to monitor these movements regularly with manual measurements*." Thanks to digital measurements, we can now quantify the building's behavior.

When participants' narratives are considered collectively, it becomes evident that digital technologies are understood not merely as tools that ensure technical accuracy but as mechanisms that engender epistemic confidence in expert decision-making. Engineering-oriented participants in particular emphasized that digital data contribute to more objective assessments in structural risk analyses by reducing differences in interpretation. However, some experts believe that numerical data alone may not be sufficient and that physical experience of the structure remains decisive. P5's observation that "*the model shows you the crack, but sometimes you can only understand in the* *field why the material has behaved in that way*" draws attention to the complementary relationship between digital analysis and on-site observation. This approach demonstrates that participants view digitalization not as an alternative to traditional expertise, but as a hybrid conservation practice that supports field experience.

Some participants noted that the risks made visible by digital systems have created a new awareness in conservation processes. The ability to track, over time, changes in small deformations that were previously considered "insignificant" has changed how experts view structures. P13 describes this transformation as follows: "*Before, we would note a small surface movement and move on, but now, because we can compare the change over the years, we can see that movement might actually be the beginning of a significant structural process*." This statement reveals that digital technologies do not merely serve as tools for documenting a structure's current condition, but also create a new mode of thinking in conservation practice by making a structure's behavior over time visible.

3.1.2. Data-Driven Decision-Making Processes

Participants stated that digital systems have significantly changed the way decisions are made in conservation processes, and, in particular, that they contribute to a more systematic justification of intervention decisions. Experts considered the ability of HBIM and digital twin applications to bring together multi-layered data on a structure's history on a single platform an advantage that ensures "memory integrity" in conservation processes. P1's statement that "*because we can see all the interventions on the model in chronological order, we are more confident in our decisions*" demonstrates that experts experience digital data archives not merely as a technical convenience but as a system that enhances decision security. Some participants emphasized that digitalization has particularly changed the understanding of risk management. P12 noted that sensor-based systems enable the continuous monitoring of structural behavior, stating, "*Before, we would intervene after we saw the damage. Now, with data from the sensors, we continuously track the building's behavior and can determine the timing of intervention accordingly.* This demonstrates that participants regard digital technologies not merely as tools for documenting existing damage, but as strategic systems that help anticipate risks that may arise in the future.

On the other hand, digital data production has also been observed to create new forms of accountability in decision-making processes. It was stated that, particularly in large-scale restoration projects, decisions can no longer be justified solely on the basis of professional experience. P17's assessment that "*numerical data and model-supported analyses allow the decision to be scientifically defended*" suggests digitalization is strengthening a culture of accountability in the conservation field. A noteworthy point here is that experts use digital data not only for technical verification, but also as a tool for producing institutional legitimacy.

However, some participants indicated that data intensity does not always facilitate decision-making. Determining which data are truly critical can sometimes be difficult in projects with multi-layered data streams. P8's statement that "*sometimes so much data comes in that it becomes hard to decide which indicator should be prioritized for intervention*" demonstrates that data-driven systems also create new interpretive burdens. This reveals that digital transformation necessitates not only data production, but also the capacity to make sense of data.

3.1.3. Transition from Traditional Inspection to Digital Monitoring

Participant narratives demonstrate that digital technologies are transforming the inspection paradigm in cultural heritage sites from a periodic review approach to a continuous monitoring model. Experts regarded the ability to track structural behavior in real time through sensor systems, particularly digital twin applications, as a significant paradigm shift in conservation practice. P6's statement that "*now, with sensors, the building continuously produces data and we can see risks at an early stage*" reveals that experts associate digital monitoring systems with the capacity for early intervention.

This transformation becomes more pronounced in the narratives of experts working in high-disaster-risk areas. P8, noting that tracking small structural movements over time plays a critical role in preventing large-scale damage, stated: "*Especially in buildings at risk of earthquakes, monitoring the change in small movements over time is very important*." Sometimes a movement that is not noticeable to the eye can be a harbinger of serious structural problems in the future. Thus, the temporal dimension of conservation approaches is also changing; the traditional understanding based on post-damage intervention is giving way to a logic of continuous observation and early warning.

Some participants noted that digital monitoring systems have also transformed experts' relationships with structures. P14 stated, "*before, we would visit the building at certain intervals and make assessments. Now the building is continuously sending us data and in a sense telling us its own condition,*" pointing out that digitalization has redefined the structure-expert relationship. This narrative demonstrates that digital technologies are not merely data collection tools but generate a new conservation logic that makes it possible to monitor structures "live.

However, more cautious assessments of the digital monitoring approach exist. Some experts emphasized that continuous data production requires sustainable management capacity. P19's statement that "*managing the technology sustainably is as serious a matter as setting it up*" demonstrates that digital transformation extends beyond investment in technical infrastructure. The effectiveness of digital systems may diminish in the absence of continuous data flow, expert human resources, maintenance processes, and institutional coordination. Accordingly, participants recognize that while digital monitoring systems offer significant advantages, the sustainability of this transformation is directly linked to institutional adaptive capacity.

3.2. Technical and Operational Challenges in Digital Risk Inspection Processes

This theme focuses on the technical, operational, and institutional challenges that arise during the implementation of digital risk-inspection systems at cultural heritage sites. An examination of participant narratives reveals that while the significant contributions of digital technologies to conservation processes are acknowledged, multilayered problems emerge during implementation. Participants considered software incompatibility, data intensity, shortage of expert human resources, and, in particular, field applicability issues to be the main obstacles to digital transformation. Participants emphasized that despite increasing technological capacity, implementation processes remain heavily dependent on human expertise and interdisciplinary coordination.

3.2.1. Software Incompatibility

Participants stated that although digital systems used in cultural heritage projects are theoretically designed to operate in an integrated manner, they contain serious incompatibilities in practice. Experts considered data-format problems encountered during data transfer—particularly among HBIM, GIS, laser-scanning software, and structural-analysis programs—to be one of the primary issues slowing project processes. P2 noted that data loss occurs across different platforms, stating, "*when you transfer a model created in one software to another platform, some data may be lost*," and emphasizing that loss of detail in historic structures can directly affect conservation decisions. This is seen not merely as a technical problem, but as a critical risk area that can lead to loss of the structure's original information.

Some experts noted that software incompatibility creates larger time losses in day-to-day work processes than are visible on the surface. P15, noting that data integration processes create significant operational delays in practice, stated: "*Matching the scanning data with the analysis model can sometimes take days*." Because each system operates with a different data logic, we must make repeated adjustments within the same project. The use of different software infrastructures by interdisciplinary teams, in particular, makes the joint production of data more difficult and fragments project processes. This fragmented structure reveals that digitalization cannot be resolved by technology investment alone but instead requires standardization, data interoperability, and shared digital protocols.

Some participants approached the problem more from an economic perspective. In particular, differences in institutional capacity prevent the formation of a common digital ecosystem. P11's assessment: "*because license costs are very high, everyone works with different systems*" demonstrates that software fragmentation is related not only to technical preferences but also to budget policies. Therefore, the incompatibilities arising in digital transformation processes are understood to stem not only from engineering problems but also from structural factors such as economic sustainability and institutional resource distribution.

Some participants believe that open-source systems and common data standards could reduce this problem in the long term. P8, emphasizing that common data protocols are becoming increasingly important, particularly in international projects, stated: "*Even if different software is used, there needs to be a convergence on the same data standard.*" Otherwise, interdisciplinary collaboration becomes a recurring problem in every project. This approach demonstrates that technological progress in digital conservation processes is not merely a matter of producing new tools but also of building a shared working culture.

3.2.2. Data Density and Data Management Problems

Participants regarded the large-scale data produced in digital conservation processes as both an important advantage and a new operational burden. High-resolution scans, photogrammetric models, and, in particular, the continuous data streams obtained from sensor systems make data storage and interpretation increasingly complex. P4, noting that scanning data produced for some historic structures can reach terabyte levels, stated:

"*The total scanning data for one building can sometimes reach incredible volumes.*" Collecting the data is no longer as difficult as it used to be, but processing, cleaning, and making that data meaningful takes a significant amount of time. This assessment suggests that while digitalization has democratized data production, it has not equally advanced the capacity for data interpretation.

Another noteworthy point in participants' narratives is that data abundance sometimes complicates decision-making processes. P13, noting that data management in long-term monitoring projects has become a distinct area of expertise, stated: "*Keeping the data pool accumulated over the years organized is becoming increasingly difficult.*" As data grow, making decisions sometimes becomes harder rather than easier: distinguishing which information should be prioritized becomes more complex. Similarly, P7's remark that "*it becomes harder to identify which information is truly critical*" drew attention to the cognitive burden that digital systems can place on experts. These narratives demonstrate that large-scale data production does not always lead to more effective conservation; rather, the capacity to filter, prioritize, and interpret data is decisive.

Some experts linked the data management problem to the issue of institutional memory. Serious information loss can occur in long-running restoration projects if data are not regularly archived. P10's assessment that "*if data produced in one project cannot be read by another team years later, that data cannot truly be said to have been preserved*" reveals that sustainable accessibility of digital data is critical to conservation processes.

In this context, participants believe that digital transformation is not limited to the use of advanced equipment but is a multi-layered process requiring a culture of data management, archiving strategies, and institutional coordination.

3.2.3. Shortage of Technical Experts

Participants reported that a major problem in implementing digital risk inspection systems is the shortage of qualified experts. In particular, processes such as HBIM modeling, laser scanning analysis, and interpretation of sensor data require advanced technical knowledge. P16's statement that "*it is easy to buy the technology, but finding a team that can use it correctly is very difficult*" demonstrates that digital transformation cannot be achieved through hardware investment alone. The limited number of specialized technical personnel focused on historic structures directly affects the implementation capacity of digital systems.

Some participants believe that the problem is not only about the number of experts but also connected to the process of professional transformation. P3, stating that many experts in the conservation field are accustomed to working with traditional methods, used the following expression: "*Many experts have been working in the field with classical methods for years. Transitioning to digital systems can sometimes create a rupture that changes not just technical practices, but professional habits.*" This narrative demonstrates that digitalization entails a cultural transformation as much as a technical one. The use of digital systems requires not only learning new tools but also changing working habits and professional reflexes.

The generational knowledge gap was also among the topics frequently raised by participants. P18 noted that younger experts are more proficient in using software but may lack experience in interpreting historical context: "*Young teams learn the software very quickly, but sometimes they may have difficulty reading the historical layers of the structure*. Experienced experts know the building very well, but may approach digital systems with more reserve. This assessment demonstrates that technical knowledge and cultural heritage expertise do not always converge in the same person.

Some participants believe that hybrid expertise models will come to the fore. P1, emphasizing that professional competencies in the conservation field are undergoing transformation, stated: "*Restoration knowledge alone is no longer sufficient.*" Data analysis, model reading, and interpretation of digital systems are becoming a natural part of the profession. This approach demonstrates that digital transformation is generating new expertise profiles in the cultural heritage field.

3.2.4. Field Applicability Issues

Participants stated that while digital risk inspection systems perform well under laboratory conditions, they encounter various limitations in field conditions. The physical characteristics of historic structures, high visitor traffic, and environmental conditions can directly affect digital applications' effectiveness. P9, noting that narrow spaces and difficult-to-access sections, in particular, make data collection processes more challenging, stated: "*In some buildings there are very narrow passages, sections with low light, or points that are physically difficult to reach.*" This can affect both the duration of the scanning process and the quality of the data." This narrative demonstrates that the physical character of historic structures can limit the operational capacity of digital systems.

Notably, data collection processes become more complex in actively used historic structures. P6, pointing out that measurement processes cannot proceed uninterrupted in continuously used structures such as mosques, stated: "*In buildings with heavy visitor traffic, we sometimes cannot provide the necessary controlled environment for measurement*." Human movement can directly affect data quality. This demonstrates that because cultural heritage sites are living spaces, digital inspection processes have different dynamics from those of standard engineering projects.

Some experts highlighted the sensitivity of technological equipment to environmental conditions. P14, noting that sensor systems in particular can be affected by the variable environmental conditions of historic structures, explained: "*Humidity, temperature, or environmental vibrations can directly affect the performance of some sensors*." Because historic structures do not always provide a controlled environment, measurements can fluctuate. This assessment reveals that digital systems cannot always fully adapt to field realities. In particular, the limited climate control in historic structures can reduce the reliability of technological equipment.

Participants also noted that conservation regulations can restrict some digital applications. P5, noting that the physical interventions required to place devices in some structures cannot be carried out because of conservation principles, stated: "*Sometimes even a small intervention is needed to place a sensor, but conservation regulations may not allow it. Not every application that is technically possible is feasible in the field*. This demonstrates that the technical capacity of digital technologies does not always imply unrestricted application; conservation ethics and limits on intervention are determinative in this process.

Overall, while participants acknowledge that digital risk inspection systems offer significant advantages, they believe that successful implementation depends not only on technology but also on the joint management of multi-layered elements such as field realities, expert capacity, economic sustainability, and institutional adaptation.

3.3. Professional Perceptions and Expectations Regarding the Future of Digitalization

This theme covers experts' assessments, expectations, and professional projections regarding the future of digital technologies in cultural heritage conservation. Participants believe that digital transformation is not only changing current implementation processes but will also reshape working methods, definitions of expertise, and institutional structures within the conservation discipline in the future. AI-assisted analysis systems, digital twin technologies, and, in particular, data-driven conservation models are seen by participants as the core components of the future conservation paradigm. At the same time, experts share the view that technological advances cannot fully replace human interpretation.

3.3.1. Digital Twin and Artificial Intelligence Expectations

Participants believe that digital twin technologies will fundamentally transform conservation processes in the field of cultural heritage. Many experts considered the continuous production of data by structures using sensor systems and the interpretation of this data through AI-assisted analyses the next phase of conservation practice. P2, noting that historic structures will not simply remain archived objects, stated: "*In the near future, historic structures will not merely be preserved buildings.*" They will become living systems that continuously produce data and monitor their own behavior. This assessment demonstrates that participants perceive the digital twin concept not so much as a static modeling technique as a dynamic monitoring framework. In these narratives, technology is imagined not only as a tool for detecting damage, but as a system that continuously learns a structure's behavior and can anticipate future risks.

Some experts noted that artificial intelligence offers an analytical capacity that can exceed the limits of human intervention, particularly in large-scale heritage sites. P11, emphasizing that risky areas can be predicted through analysis of past deterioration patterns, stated: "*Artificial intelligence can analyze past damage data to predict in advance where risks may develop.*" This could make maintenance planning much more strategic, especially in large-scale heritage sites. Participants' indicate that they associate the future of digitalization more strongly with "predictive conservation. Data-driven prediction mechanisms in particular are thought capable of transforming conservation processes from reactive intervention to early warning systems.

However, optimistic expectations toward technology are not shared unconditionally by all participants. Some experts emphasized that cultural heritage is too multi-layered a field to be managed through algorithms alone. P7, who stated that technical analyses alone would not be sufficient, drew attention to this limitation: "*An algorithm can tell you the risk level of a crack, but interpreting how the intervention will affect the historic identity of the building still requires human expertise.* This approach demonstrates that participants regard artificial intelligence not as an autonomous decision-making system but as an assistive tool supporting human interpretation.

Some participants believe that artificial intelligence systems will give rise to ethical debates. P14 noted that even how the algorithm defines certain data as "risk" can influence conservation approaches and stated, "*Whatever the system identifies as the priority risk determines the intervention decisions accordingly*." Therefore, it is not possible to say that algorithms are completely neutral. This assessment demonstrates that technological progress is perceived not only as a technical advancementbut also as a political process related to the production of cultural values.

3.3.2. The Role of Human Expertise

A significant proportion of participants believe thatdespite the acceleration of digitalization, human experience will retain its central importance in cultural heritage conservation. Experts in particular stated that historic structures cannot be understood solely from numerical data; the behavior of materials, spatial atmosphere, and historical layers can often only be understood through direct field experience. P15's assessment that "*the model can be very powerful, but you cannot feel some things without walking through the building*" reveals that physical experience remains indispensable in conservation practice.

In contrast, some younger experts believe that digital tools have made professional decision-making processes more transparent. P4 noted that, in the past, many decisions were based on personal experience, but intervention processes have now become more measurable thanks to digital data. This approach demonstrates that younger experts understand digitalization as a tool that strengthens professional objectivity. Thus, the participant narratives reveal not only differences in opinion regarding technology but also generational differences in professional perceptions.

Some participants do not regard human experience and digital technology as opposing elements. P18's statement that "*the best results emerge when technology and field experience come together*" clearly articulates a hybrid approach to expertise. In these narratives, technology is positioned not as a system that replaces expertise, but as a complementary tool that makes experiential knowledge more visible and systematic.

On the other hand, some experts offered more cautious assessments about the possibility that digitalization could create a new hierarchy of expertise in the conservation field. P5 noted that experts who can use digital tools have become more prominent in decision-making processes, while those with traditional field experience sometimes find themselves in the background. This demonstrates that digital transformation is not only a technical change, but also a social process that transforms professional power relations.

3.3.3. Need for Training and Institutional Transformation

Participants stated that existing training models and institutional structures need to be reconsidered in order for digital conservation processes to become sustainable. Notably, university programs do not give sufficient attention to digital heritage technologies, and the majority of experts develop digital skills through individual effort during their professional lives. P9, noting that during their restoration education at university, HBIM and digital twin technologies were barely mentioned, stated: "*When we were studying restoration at university, systems like HBIM or digital twin were mentioned only very briefly*." After entering the field, we were forced to learn these technologies independently. This narrative demonstrates that the academic infrastructure has not been fully able to keep pace with the speed of the sector's transformation.

Some participants linked the training problem not only to a lack of technical knowledge but also to a lack of interdisciplinary thinking skills. P12, drawing attention to the knowledge gap between the conservation field and technical disciplines, stated: "*Conservation students often have difficulty understanding engineering-based digital systems. Technical experts, on the other hand, may fall short in reading the historical and cultural layers of a structure*." These statements demonstrate that digital transformation cannot be resolved merely by training people to use new software; it requires training models that bring different disciplines together within a shared working culture.

At the institutional level, it was frequently emphasized that digitalization extends beyond software investment. P13, drawing attention to the organizational dimension of digital transformation, explained, "*Buying software for an institution does not mean digital transformation. The entire working logic, from data production to archiving, needs to change*. According to participants, in institutions where the processes of data production, archiving, sharing, and decision-making have not been restructured, technological investment alone does not produce sustainable results.

Some experts noted that significant inequalities exist between public institutions and the private sector in terms of digital capacity. P6, noting in particular that budget differences directly affect access to technology, stated: "*Very advanced digital systems can be used in large-scale projects, but many small-scale conservation efforts are still progressing with traditional methods*." This demonstrates that digitalization has not spread homogeneously across the cultural heritage field and that economic resources directly determine access to technology. For participants, digital transformation is experienced as a multi-layered process with technical, economic, and institutional dimensions.

3.3.4. The Future Conservation Paradigm

Participants generally believe that the understanding of cultural heritage conservation will be transformed into a more data-driven, interdisciplinary structure based on continuous monitoring. It was noted, in particular, that the preventive conservation approach would be strengthened and that large-scale data analyses would reshape intervention strategies. P20's statement that the conservation field will no longer consist solely of restoration practices — and that processes such as data analysis, sensor management, and digital modeling will become a natural part of the profession — demonstrates that experts are thinking about the future within a broader technical-ecological system.

Some participants noted that this transformation would also bring new ethical debates. P1's assessment that "*as technology advances, intervention capacity also increases, but the question of whether every intervention should be made will become more important in the future*" highlights the tension between technological capacity and conservation ethics. For participants, the development of digital systems increases possibilities for intervention and simultaneously complicates the question "how much intervention should be carried out.

Some experts believe that in the future, conservation practice will become more collective and interdisciplinary. P16, noting that digitalization is bringing different areas of expertise together on a common working platform, stated: "*It is no longer sufficient to proceed with just an architect or restoration expert*." Data scientists, software developers, and conservation experts are required to work together within the same project environment. This assessment demonstrates that digitalization is not only producing new tools but also changing the organizational structure of the conservation discipline.

Nevertheless, the majority of participants agree that the future conservation paradigm should not be entirely technology-centered. P3, while acknowledging that digital systems have accelerated many processes, drew attention to this limitation: "*Technology makes many things easier, but it is not possible to read the meaning of cultural heritage solely through data*." Understanding the historical spirit of a structure still requires human interpretation. This approach demonstrates that, although participants accept digitalization as inevitable, they believe human experience, ethical sensitivity, and cultural context will remain the fundamental components of conservation practice.

4. DISCUSSION

The findings of this research indicate that digital technologies are experienced in cultural heritage conservation not merely as technical tools but as elements that transform the epistemological structure of conservation practice. Participant narratives have revealed, in particular, that digital scanning, HBIM, and sensor-based monitoring systems make risks in historic structures visible. This finding is consistent with the literature emphasizing that digital technologies in the cultural heritage field have evolved beyond documentation to become decision-support systems. Murphy et al. (2009) note that the HBIM approach enables the comprehensive management of not only the geometric representation of historic structures, but also historical, structural, and material data related to the building. Similarly, Bruno and Roncella (2019) note that laser scanning and photogrammetric modeling techniques increase the level of measurability in conservation processes by revealing deformations in complex historic structures that would otherwise remain invisible. The fact that participants in this study describe digital systems as structures that "make the invisible visible" demonstrates that conservation practice is shifting from intuitive assessments toward a data-driven monitoring logic.

One of the important findings of the research is that digital technologies transform the mode of decision-making in conservation processes. Participants reported that HBIM and digital twin applications enable comprehensive monitoring of past interventions, current risks, and structural changes from a single platform. This demonstrates that conservation processes are shifting from reactive intervention to preventive conservation. The literature also emphasizes that digital conservation systems strengthen the capacity for early intervention in risk management. Masciotta et al. (2021) note that digital data-based conservation approaches reinforce the preventive conservation understanding by shifting maintenance processes toward a continuous monitoring logic. Participants in this study interpreted the capacity of sensor data, in particular, to enable real-time monitoring of structural behavior as an "early warning mechanism. This finding suggests that digitalization in the cultural heritage field is not merely technical modernization but rather creates a new conservation paradigm that transforms the perception of time.

The findings also show that digitalization is transforming the understanding of scientific legitimacy and institutional accountability in conservation processes. Participants stated that digital models make intervention decisions more transparent and defensible. Notably, digital archiving systems strengthen institutional memory in large-scale restoration projects. This is consistent with Zhou's (2024) assessment that standardized digital workflows in the cultural heritage field are critical for institutional sustainability. Digital data production contributes to evaluating intervention processes not only in terms of technical accuracy but also in terms of documentability and traceability.

The second main theme of the research—technical and operational challenges— reveals that digital transformation processes do not proceed in a linear or unproblematic manner. Participants emphasized that software incompatibilities and data transfer problems, in particular, create significant delays during implementation processes. This finding is consistent with studies highlighting interoperability problems in the cultural heritage field. Rocha et al. (2020) highlight that the lack of common data standards across platforms leads to interoperability problems in HBIM processes, resulting in data loss and operational interruptions. Participants in this study also stated that different software infrastructures make interdisciplinary coordination more difficult and fragment project processes. Therefore, digital transformation can become sustainable only through the development of common data standards, not through the mere adoption of new technologies.

Data density and data management problems are also among the striking findings of the research. Participants noted that high-resolution scanning systems and sensor networks that continuously generate data create large-scale data pools, but interpreting these data is becoming increasingly difficult. This demonstrates that digitalization not only produces technical advantages but also creates new cognitive and operational burdens. The literature notes that big data management is generating new expertise requirements in the cultural heritage field (Bruno & Roncella, 2019). In this study, too, participants emphasized that data production alone is not meaningful, and that the truly critical issue is filtering and integrating data into decision-making processes. Thus, digital conservation processes are related not only to hardware capacity but also to data management culture.

Another significant finding of the research is that the shortage of technical experts is a distinct problem in digital risk inspection processes. Participants stated that qualified human resources are particularly limited in HBIM modeling, sensor data analysis, and digital scanning processes. This finding demonstrates that digital transformation in the field of cultural heritage is simultaneously a process of professional transformation. Experienced conservation experts trained in traditional methods, in particular, may find the process of adapting to digital systems more difficult. Conversely, young experts appear stronger in terms of technical proficiency but may lack experience in historical context and conservation ethics. This suggests that hybrid expertise models will gain importance in the future. Murphy et al. (2009) emphasize that HBIM processes need to be carried out not with technical modeling knowledge alone, but together with knowledge of architectural history and conservation. The findings of this research also reveal that the integration of technical knowledge and cultural heritage expertise is critical for sustainable digital transformation.

The final theme of the research, "Professional Perceptions and Expectations Regarding the Future of Digitalization," indicates that participants believe digital twin and AI systems will become more central to conservation processes. The prior prediction of structural risks, and in particular the automation of maintenance planning, were considered by participants to be among the core components of the future conservation paradigm. The literature notes that digital twin technologies hold significant potential for real-time monitoring and risk prediction in the cultural heritage field (Wang et al., 2023). However, participants in this study particularly emphasized that cultural heritage cannot be managed through purely algorithmic processes. Human experience, knowledge of historical context, and ethical evaluation processes are expected to remain decisive. This finding demonstrates that technological progress transforms, rather than eliminates, conservation expertise.

Participants also noted that digitalization will require transformations in educational systems and institutional structures. The findings show that existing university programs have not been sufficiently integrated with digital heritage technologies and that many experts are compelled to acquire digital skills through individual effort during their professional lives. This reveals the need for interdisciplinary education models in the cultural heritage field. In particular, data analysis, HBIM, GIS, and digital twin technologies need to become core components of conservation education. Likewise, it is evident that institutional transformation is possible not only through technology investment but also through a data management culture, organizational adaptation, and interdisciplinary collaboration.

Overall, this research demonstrates that digitalization in the conservation of cultural heritage does not create a linear technological progression but rather a multi-layered transformation with technical, institutional, economic, and professional dimensions. Digital technologies strengthen measurability, support continuous monitoring, and increase capacity for data-driven decision-making in conservation processes. However, software incompatibilities, data management problems, shortages of experts, and differences in institutional capacity are hindering the sustainability of digital transformation. For this reason, it is believed that the future conservation paradigm in the field of cultural heritage should be built on a balanced structure that centers not on technology alone but on human expertise, ethical sensitivity, and interdisciplinary collaboration.

5. CONCLUSION

This study has examined how digitally based risk inspection processes in historic and monumental structures transform conservation practices, what technical and operational problems arise during implementation, and how experts make sense of their professional expectations regarding the future of digitalization. The research findings demonstrate that digital technologies do not merely offer new technical tools in cultural heritage conservation, but also create a multi-layered transformation that restructures the understanding of conservation, the logic of intervention, and relations of expertise. In particular, HBIM, digital twins, laser scanning, and sensor-based monitoring systems were found to offer significant advantages in visualizing structural risks. Participants emphasized that these technologies make it possible to produce measurable, verifiable, and continuously updatable data in conservation processes. This demonstrates that conservation practice is shifting from intuitive assessments toward data-driven decision mechanisms.

One important conclusion of the research is that digital systems strengthen the "preventive conservation" approach in conservation practice. The findings reveal that the traditional approach to inspection is largely based on post-damage intervention; by contrast, digital monitoring systems increase capacity for early intervention by continuously tracking structural behavior. The ability of sensor systems, particularly digital twin applications, to enable real-time monitoring of structures is accelerating the transition from reactive approaches to proactive inspection models in risk management. This conclusion suggests that maintenance and intervention strategies for cultural heritage conservation will increasingly be shaped by data-driven predictive mechanisms.

At the same time, the study demonstrates that digital transformation processes are not limited to technical advantages. Participants stated that issues such as software incompatibility, data density, expert shortages, and field applicability create significant limitations in digital risk inspection processes. Data transfer problems between different software platforms, particularly the lack of standards, make interdisciplinary coordination more difficult, while large-scale data production brings new data management problems. The research findings reveal that digitalization cannot be sustainable through investment in technological equipment alone and must also be supported by institutional adaptation, data standardization, and skilled personnel.

The study also demonstrates that digital transformation is creating new forms of expertise in the cultural heritage field. Participants emphasized that future conservation experts will need to possess not only restoration knowledge, but also skills in data analysis, digital modeling, AI-assisted systems, and interdisciplinary coordination. This indicates that hybrid expertise models will become increasingly important in conservation. However, the research findings also reveal a strong professional perception that digital systems cannot fully replace human expertise. Participants believe that the interpretation of historical context, the evaluation of cultural values, and the ethics of interventions will continue to require human experience and expert interpretation. For this reason, the future of digitalization lies not in full technology-centered automation but in a hybrid conservation paradigm in which human expertise and digital systems work together.

Another important conclusion of the research is that digital transformation processes exert pressure on educational systems and institutional structures. The findings demonstrate that existing university programs are not sufficiently integrated with digital heritage technologies and that a significant proportion of experts are compelled to acquire digital skills through individual efforts during their professional careers. At the same time, that differences in digital capacity exist between public institutions and the private sector, and this situation creates technological inequalities in conservation processes. In this context, sustainable digital transformation requires restructuring not only technical infrastructure but also educational policies, institutional data-management culture, and models of interdisciplinary collaboration.

6. RESEARCH CONTRIBUTIONS, LIMITATIONS, AND FUTURE RESEARCH DIRECTIONS

6.1. Contributions of the Research

This study makes two primary contributions to the literature on digital risk inspection. First, the research goes beyond existing studies that evaluate digital conservation technologies solely on technical performance and instead centers on practitioners' experiences. Second, the study addresses the transformation created by digitalization in the cultural heritage field across its technical, institutional, professional, and ethical dimensions, offering a holistic evaluation. In this regard, this research offers an original perspective on the applicability of digital conservation technologies in field settings.

6.2. Limitations and Future Research Recommendations

The research does, however, have certain limitations. The study involved only experts based in Istanbul, and application experiences from other geographical regions were not included in the study's scope. Furthermore, because the research was conducted using a qualitative method, the findings reflect experts' experiences within a specific context. Future research comparing conservation policies across countries, examining the implementation performance of AI-assisted risk prediction systems, and enriching digital conservation processes with quantitative data analyses could make important contributions to the literature. In particular, the ethical dimensions of digital twin and artificial intelligence technologies in the field of cultural heritage need to be discussed more comprehensively in the future.

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